Detailed measurements of nuclear structure at high-energy colliders

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March 2, 2022

Outline

1. Nuclear structure and heavy-ion collisions

2. Nuclear deformation in large collision systems at RHIC and LHC

3. Nuclear structure in isobar collisions at RHIC

4. Conclusions and outlooks

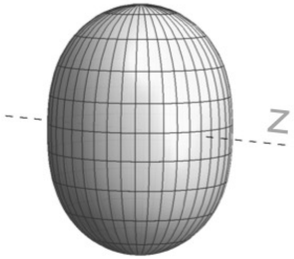
Nuclei shape, radial structure and nucleonic cluster

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

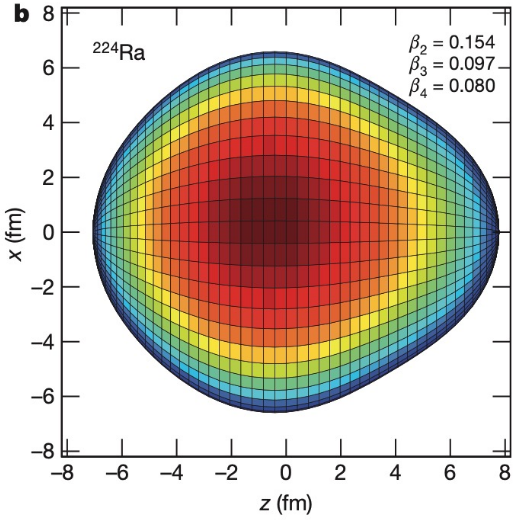
$$R(\theta,\phi) = R_0\left(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}] + \beta_3 \sum_{m=-3}^{3} \alpha_{3,m} Y_{3,m} + \beta_4 \sum_{m=-4}^{4} \alpha_{4,m} Y_{4,m}\right)$$

Quadrupole

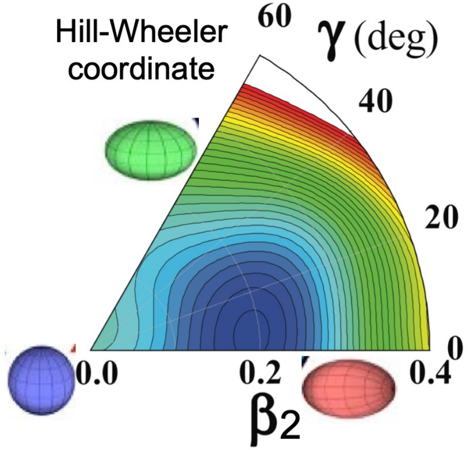
$1 + \beta_2 Y_{2,0}(\theta,\phi)$



Octupole (pear-shaped) deformation



L. O. Gaffney et al., Nature497, 199(2013)



Triaxial spheroid

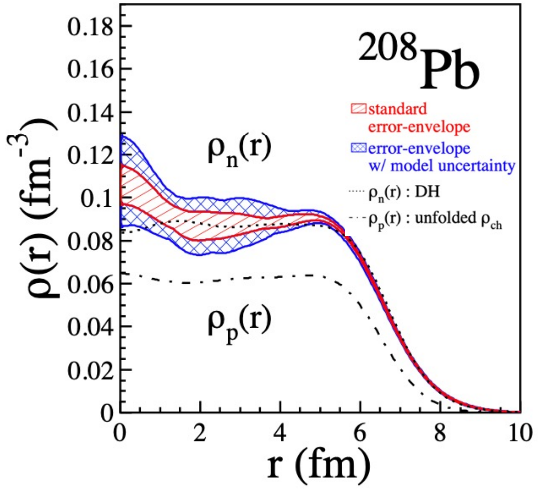
A. N. Andreyev et al., Nature405, 430(2000)

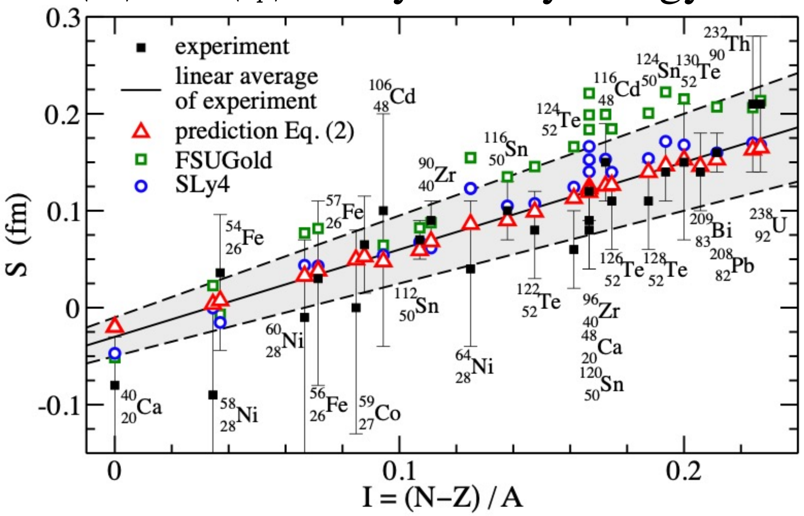
S. Cwiok et al., Nature433, 705(2005)

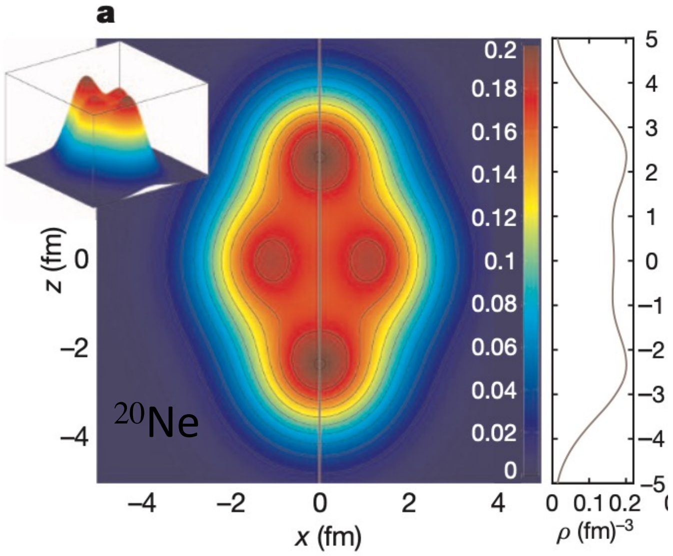
A. Trzcinska et al., PRL87, 082501(2001)

M. Centelles et al., PRL102, 122502(2009)

Neutron skin $\Delta r_{np} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$ Symmetry energy





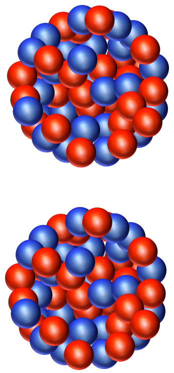


Nucleonic clustering in light nuclei

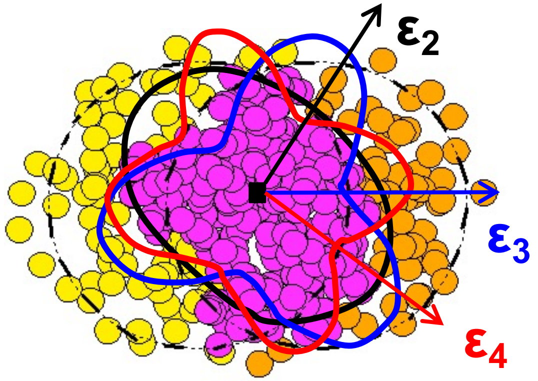
J.P. Ebran et al., Nature478, 341(2012)

Connecting the initial state to the final state: hydrodynamic response

Nuclear Structure | **Initial State** | **Produced Particle Flow**



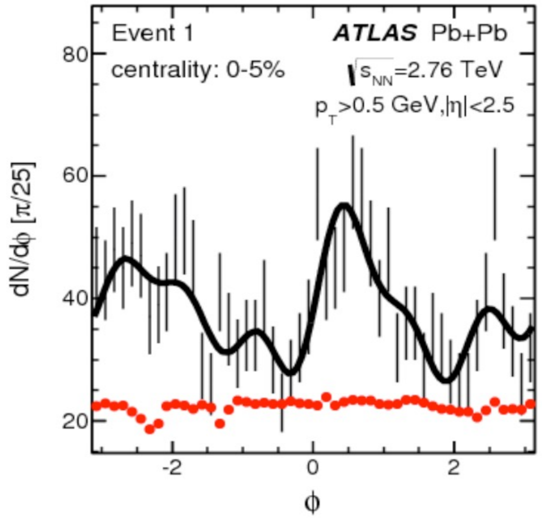
Imaging?



Hydrodynamic response

Approximate linear response in each event:

D. Teaney and L. Yan, PRC86, 044908(2012) (Editors' Suggestions)



$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{\left(r - R_0\left(1+\sum_n \beta_n Y_n^0(\theta,\phi)\right)\right)/a_0}}$$

Initial Size

$$R_\perp^2 \propto \langle r_\perp^2 \rangle$$

Initial Shape

$$\mathcal{E}_n \propto \langle r_\perp^n e^{in\phi} \rangle$$

?

R_0 a_0 β_n

Radial Flow | Anisotropic Flow

$$\frac{d^2N}{d\phi dp_T} = N(p_T)\left(\sum_n V_n e^{-in\phi}\right)$$

$\beta_2 \rightarrow$ Quadrupole deformation

$\beta_3 \rightarrow$ Octupole deformation

$a_0 \rightarrow$ Surface diffuseness

$R_0 \rightarrow$ Nuclear size

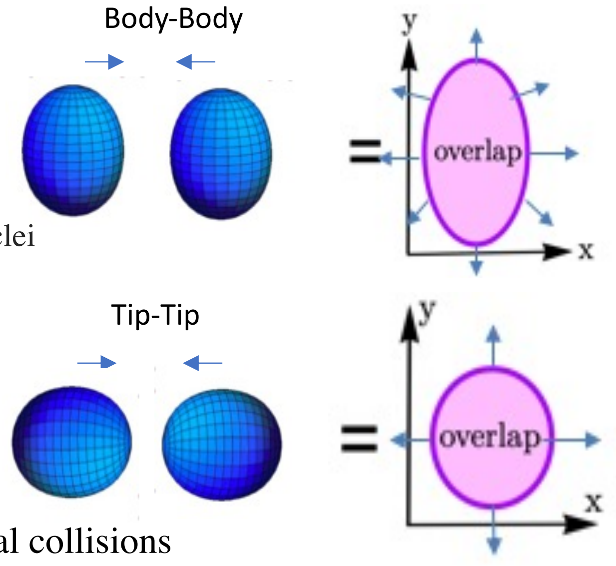
High energy: approximate linear Response in each event

$$\frac{\delta[p_T]}{[p_T]} \propto -\frac{\delta R_\perp}{R_\perp} \qquad V_n \propto \mathcal{E}_n$$

Nuclear deformation in large collision systems at RHIC and LHC

Connecting the initial state to the nuclear geometry

G.Giacalone, PRL124, 202301(2020)



Prolate nuclei

Ultra-central collisions

- $\boldsymbol{\varepsilon}_2$ and R are influenced by the quadrupole deformation β_2
- $\langle p_T \rangle \sim 1/\mathrm{R}$ and $\mathrm{v}_2 \propto \boldsymbol{\varepsilon}_2$: $\left\langle \epsilon_n^2 \frac{1}{R} \right\rangle \rightarrow \langle v_n^2\, p_\mathrm{T} \rangle$

  deformation contributes to anticorrelation between v_2 and $\langle p_T \rangle$
- $\langle p_T \rangle$ allows us to discern body-body and tip-tip collisions

Pearson coefficient: $\mathbf{v_n}$-$\mathbf{p_T}$ three particle correlator

$$\mathrm{cov}\left(v_n^2, [p_\mathrm{T}]\right) \equiv \left\langle \frac{\sum_{i\neq j\neq k} w_i w_j w_k e^{in\phi_i} e^{-in\phi_j} (p_{\mathrm{T},k} - \langle\langle p_\mathrm{T} \rangle\rangle)}{\sum_{i\neq j\neq k} w_i w_j w_k} \right\rangle_\mathrm{evt}$$

$$\rho\left(v_n^2, [p_T]\right) = \frac{\mathrm{cov}\left(v_n^2, [p_\mathrm{T}]\right)}{\sqrt{\mathrm{Var}\left(v_n^2\right)_\mathrm{dyn} \langle \delta p_T \delta p_T \rangle}}$$

$$[p_\mathrm{T}] \equiv \frac{\sum_i w_i p_{\mathrm{T},i}}{\sum_i w_i}, \langle\langle p_\mathrm{T} \rangle\rangle \equiv \langle [p_\mathrm{T}] \rangle_\mathrm{evt}$$

$\mathrm{w_i}$ is track weight

$$\mathrm{Var}\left(v_n^2\right)_\mathrm{dyn} = v_n\{2\}^4 - v_n\{4\}^4$$

$$\langle \delta p_\mathrm{T} \delta p_\mathrm{T} \rangle = \left\langle \frac{\sum_{i\neq j} w_i w_j (p_{\mathrm{T},i} - \langle\langle p_\mathrm{T} \rangle\rangle)(p_{\mathrm{T},j} - \langle\langle p_\mathrm{T} \rangle\rangle)}{\sum_{i\neq j} w_i w_j} \right\rangle_\mathrm{evt}$$

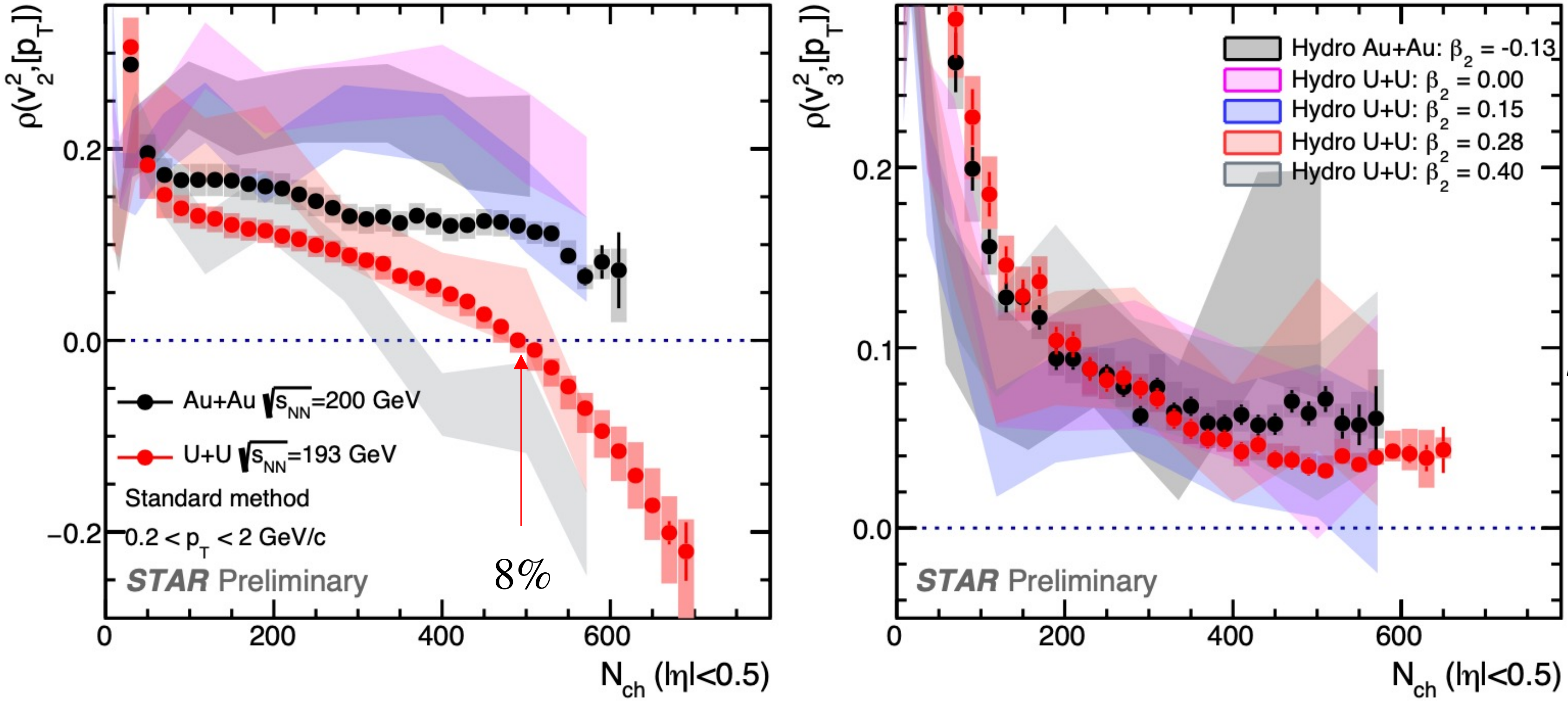
1) Insensitive to medium properties of QGP
2) Insensitive to trivial statistical fluctuation
3) Isolate the correlations coming from genuine collective effect.

Prediction: in central collisions of deformed nuclei $\rho(\mathrm{v}_2^2, [\mathrm{p_T}]) < 0$

P. Bozek, PRC93, 044908(2016); ATLAS EPJC79, 985(2019);
G.Giacalone, PRC102, 024901(2020); B. Schenke et al., PRC102, 034905(2020);

Compare to (boost-invariant) CGC+Hydro model

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke (PRC102, 044905(2020))



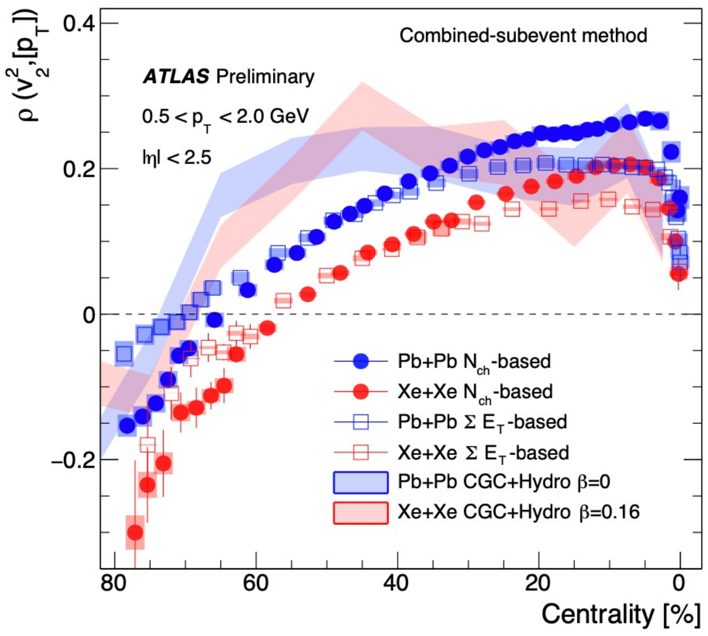
$$\rho(v_n^2,[p_T]) = \frac{\mathrm{cov}(v_n^2,[p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}}\langle\delta p_T \delta p_T\rangle}}$$

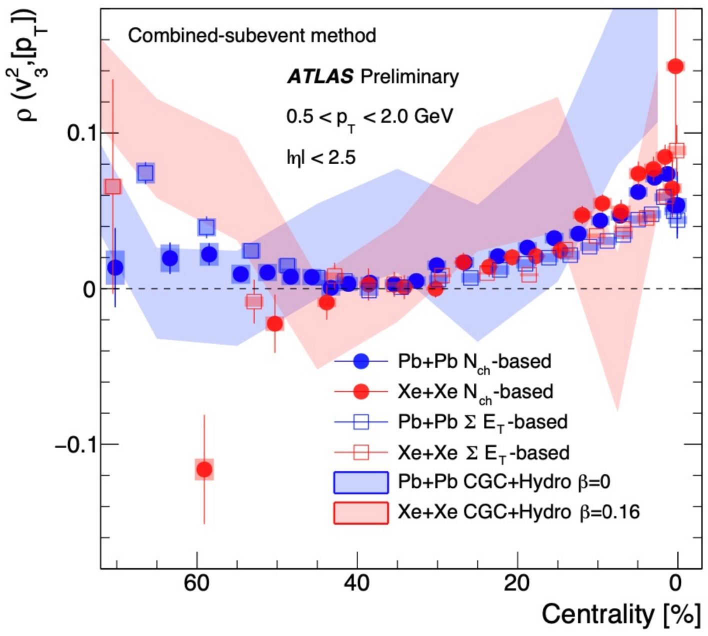
- Without deformation, CGC+hydro model shows positive $\rho(v_2^2,[p_T])$ in central.
- With increasing β_2, model could describe the trend of $\rho(v_2^2,[p_T])$.
- Model shows that $\rho(v_3^2,[p_T])$ is insensitive to β_2.

The sign-change of $\rho(v_2^2,[p_T])$ is due to deformation, model quantifies the β_2 value around 0.3 with large uncertainty.

Moving to LHC: money plots from ATLAS and ALICE

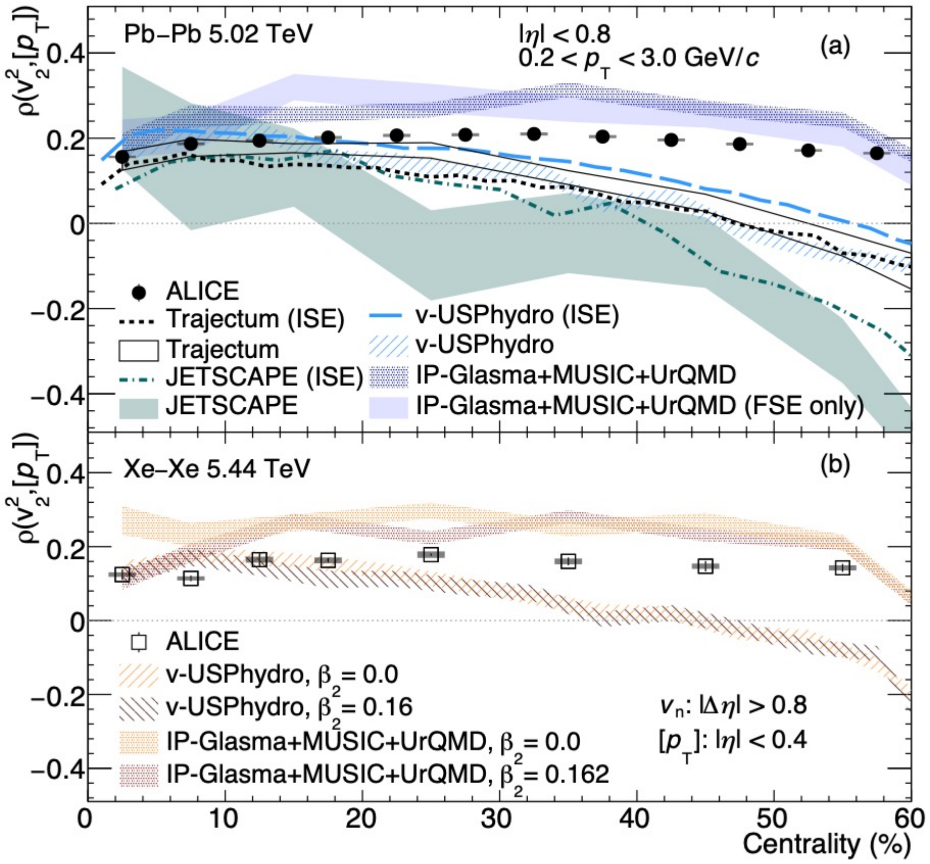
S. Bhatta, A. Behera, and J. Jia (ATLAS), IS2021





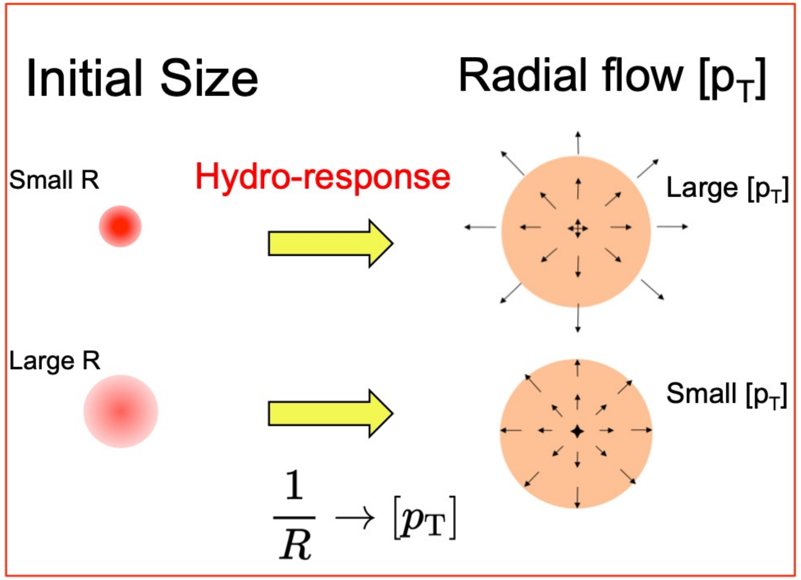
- $\rho(v_2^2, [p_T])$ has system size dependence: Pb+Pb > Xe+Xe
- $\rho(v_2^2, [p_T])$ is negative in peripheral LHC energy: geometric effect
- $\rho(v_3^2, [p_T])$ is comparable in Pb+Pb and Xe+Xe.
- CGC+Hydro qualitatively captures centrality trends of data.

Y. Zhou et al., (ALICE), arXiv:2111.06106v1



- IP-Glasma+Hydro is near to data rather than the TRENTo based calculations.
- Help to constrain the initial state.

$[p_T]$ fluctuations: a new probe of nuclear structure



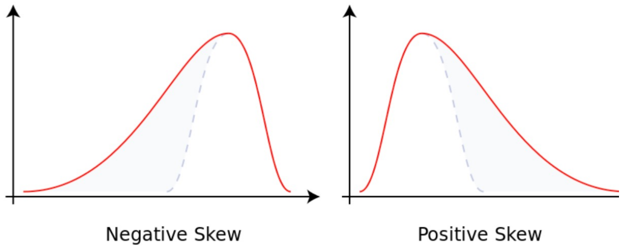
J. Jia, arXiv:2109.00604v1

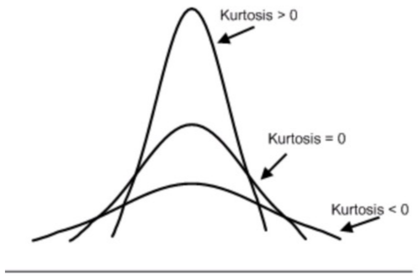
Mean $$\frac{\delta[p_T]}{[p_T]} \propto \frac{\delta d_\perp}{d_\perp} = \delta_d + p_0(\Omega_1,\Omega_2,\gamma)\beta_2 + \mathcal{O}(\beta_2^2)$$

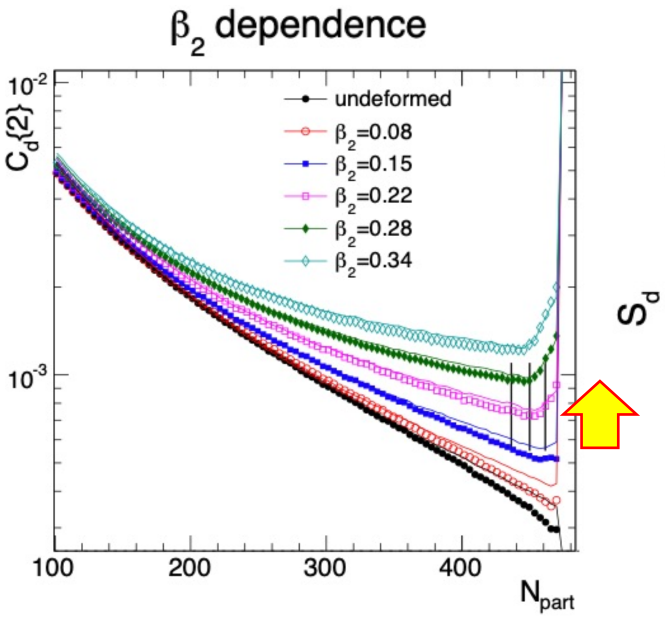
Variance $$\left\langle\left(\frac{\delta[p_T]}{[p_T]}\right)^2\right\rangle \propto \left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle = \langle\delta_d^2\rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^2\right\rangle\beta_2^2$$

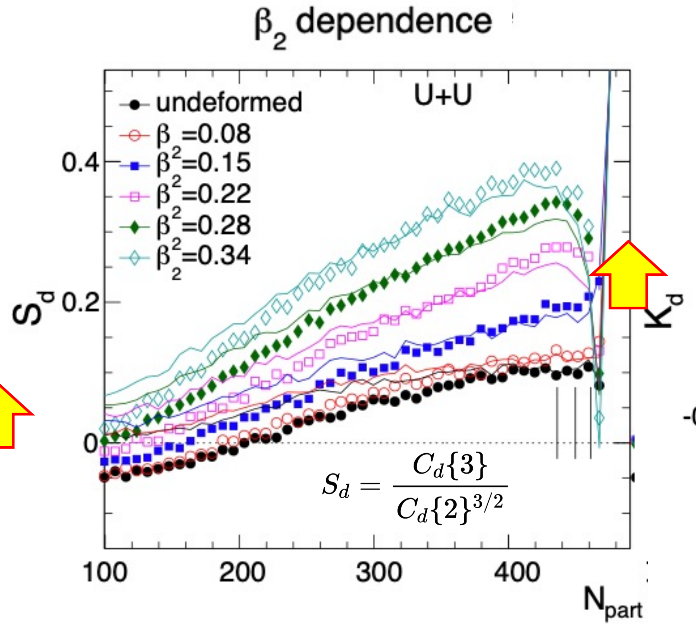
Skewness $$\left\langle\left(\frac{\delta[p_T]}{[p_T]}\right)^3\right\rangle \propto \left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle = \langle\delta_d^3\rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^3\right\rangle\beta_2^3$$

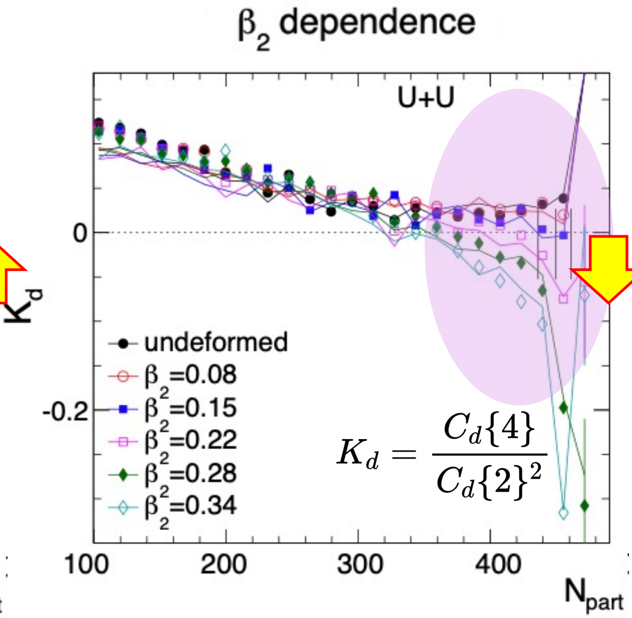
Kurtosis $$\left\langle\left(\frac{\delta[p_T]}{[p_T]}\right)^4\right\rangle - 3\left\langle\left(\frac{\delta[p_T]}{[p_T]}\right)^2\right\rangle^2 \propto \left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^4\right\rangle - 3\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle^2 = \langle\delta_d^4\rangle - 3\langle\delta_d^2\rangle^2 + \left(\left\langle p_0(\Omega_1,\Omega_2,\gamma)^4\right\rangle - 3\left\langle p_0(\Omega_1,\Omega_2,\gamma)^2\right\rangle^2\right)\beta_2^4$$







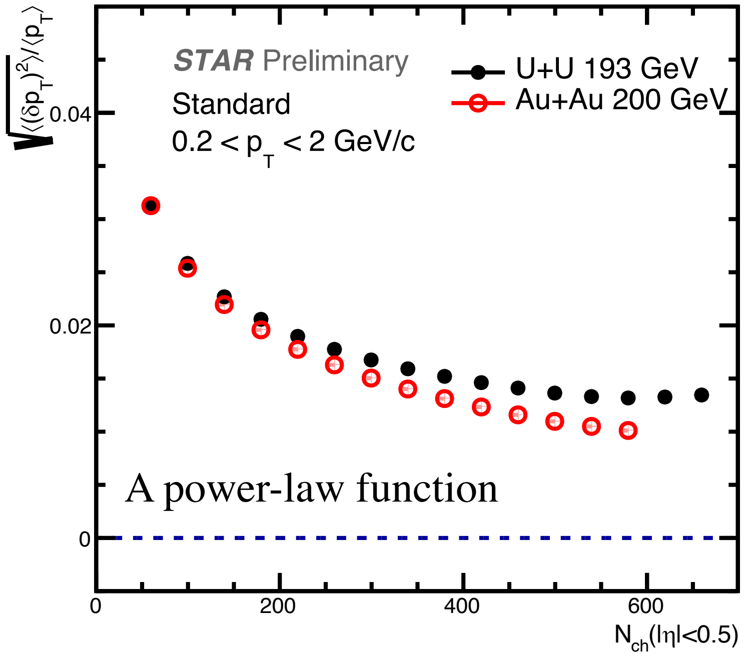


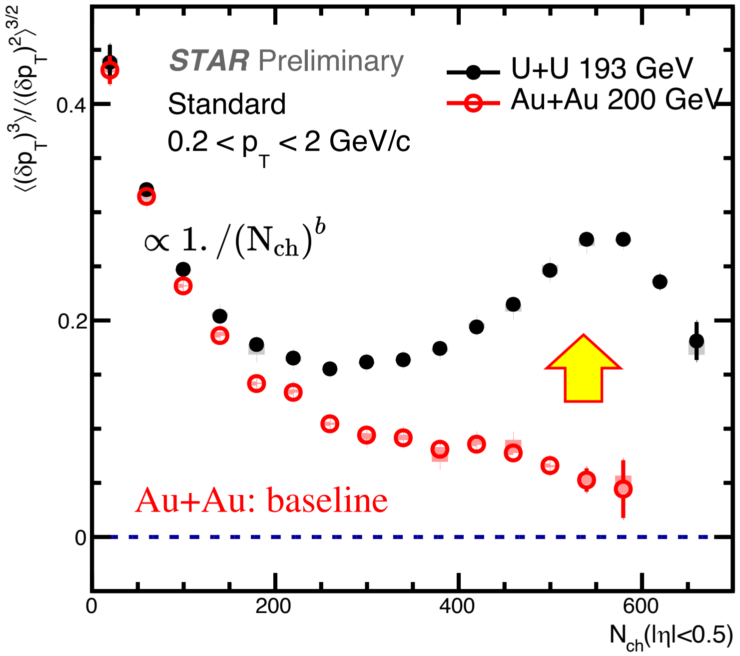


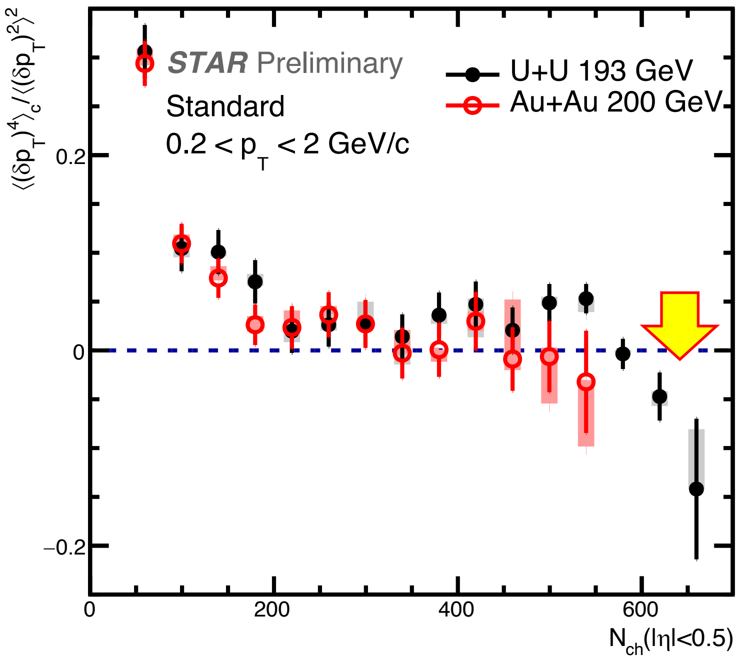
G. Giacalone et al., PRC103, 024910(2021)

S. Bhatta, C. Zhang and J.Jia, arXiv:2112.03397

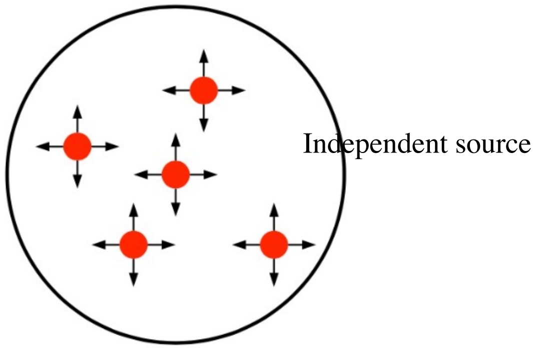
$[p_T]$ fluctuations at STAR







Radial expansion induced by nuclei shape:



Significant enhancement in central U+U

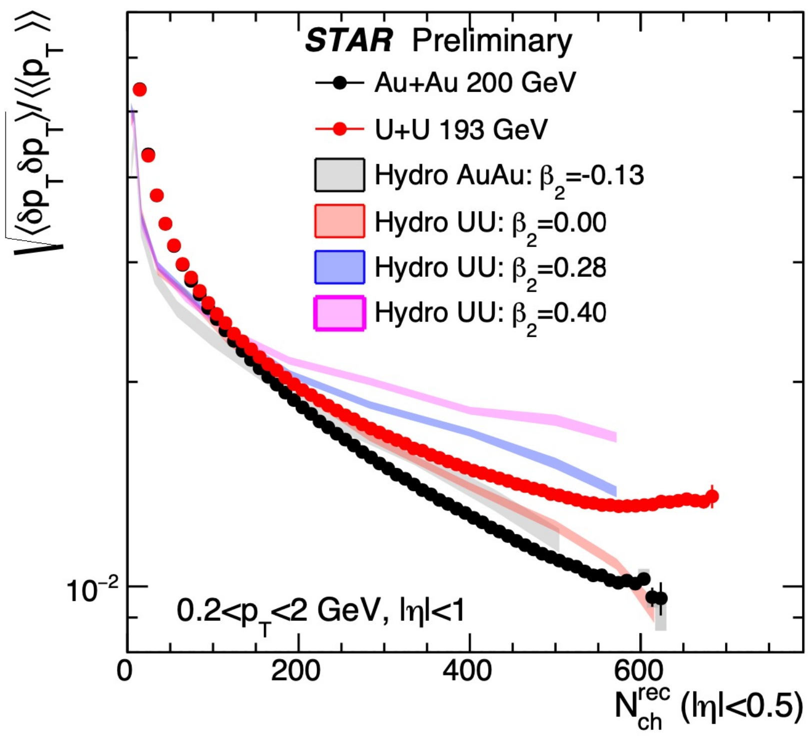
Clear sign-change in collisions of highly deformed U ions

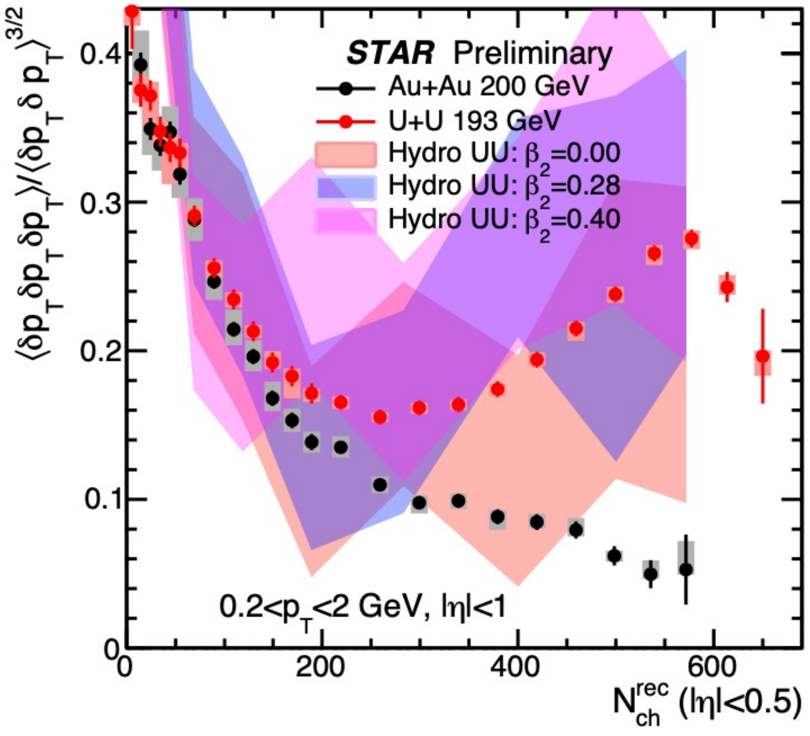
Deformation also affects mid-central and central collisions.

Uranium β_2 also have clear influence on the $[p_T]$ fluctuations

Compare to CGC+hydro model

IP-Glasma+Hydro: private calculation provided by Bjoern Schenke





Clear differences due to deformation effect are also confirmed by the IP-Glasma+Hydro .

IP-Glasma + Hydro describes data qualitatively.

An important test on the thermal equilibrium, EoS and collision geometry.

(need higher statistic hydrodynamics calculations…)

Nuclear structure in isobar collisions at RHIC

The STAR detector and unique isobar run

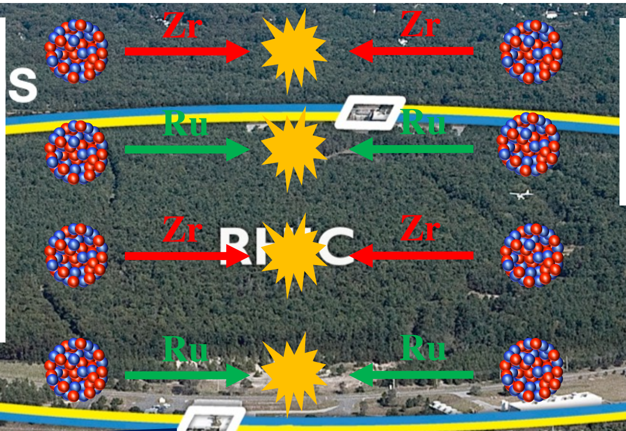
1) ${}^{96}_{44}\mathrm{Ru}+{}^{96}_{44}\mathrm{Ru}$, ${}^{96}_{40}\mathrm{Zr}+{}^{96}_{40}\mathrm{Zr}$ at $\sqrt{S_{NN}}$ = 200 GeV

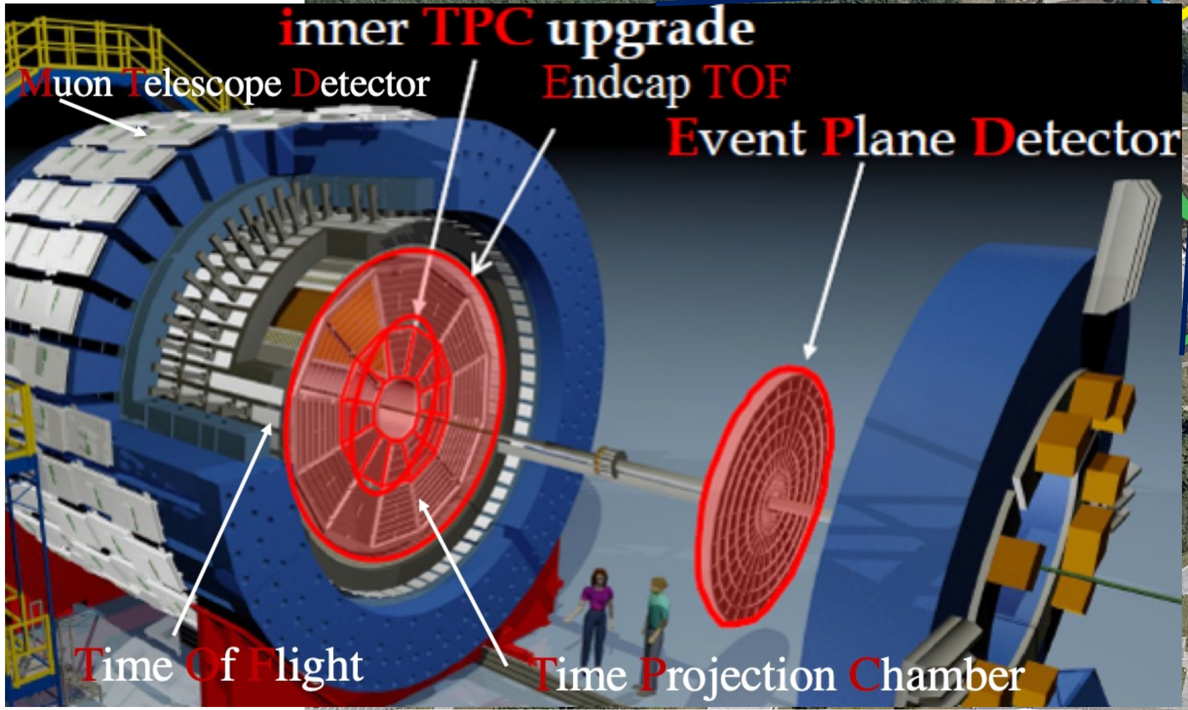
2) Special operation mode:

- Fill-by-fill switching between Ru+Ru and Zr+Zr
- Similar run conditions at STAR (minimize the systematics)

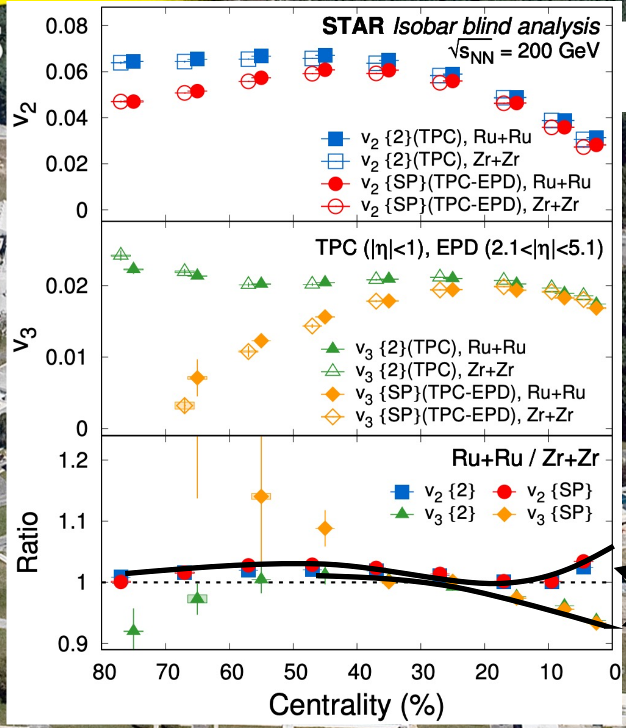
3) Ideal system to study nuclear structure:

$$\frac{\mathcal{O}_{\mathrm{Ru+Ru}}}{\mathcal{O}_{\mathrm{Zr+Zr}}} \stackrel{?}{=} 1$$





Large, uniform acceptance at mid-rapidity



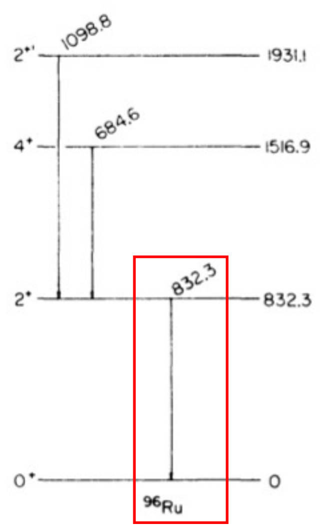
Isobar run originally dedicated to CME search

M. S. Abdallah et al. (STAR), PRC105, 014901(2022)

Significant departure from one

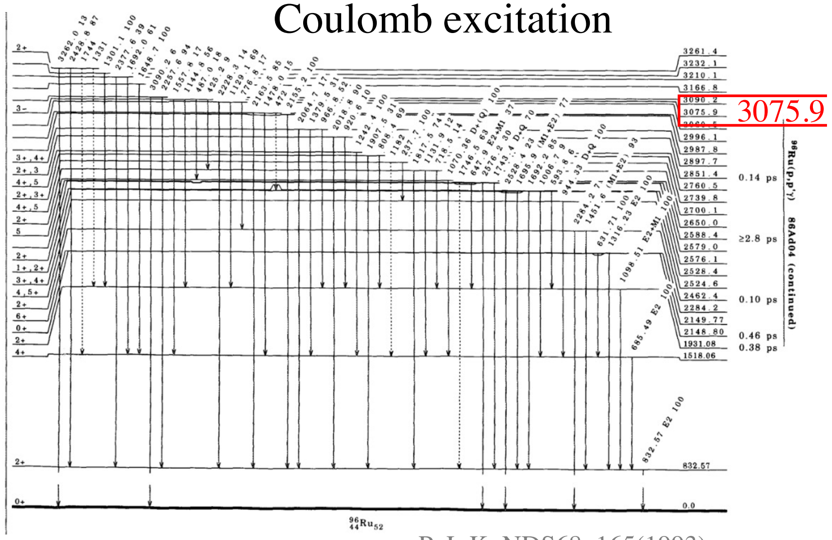
Nuclear deformation experimental data on ^{96}Ru and ^{96}Zr

^{96}Ru



S. Landsberger et al. PRC21, 588(1980)

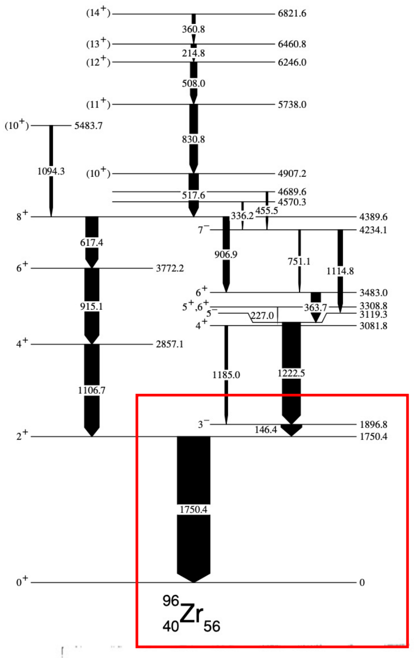
Coulomb excitation

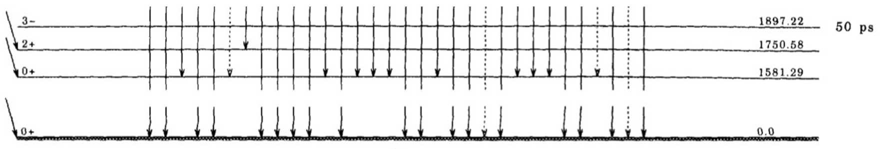


P. L.K, NDS68, 165(1993)

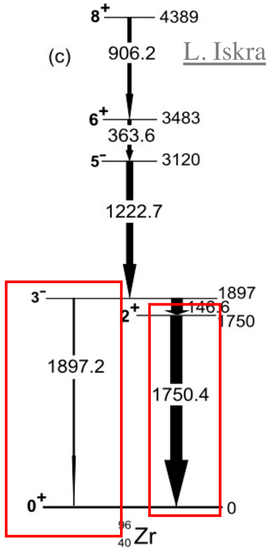
D. Pantelica et al., PRC72, 024304(2005)

^{96}Zr

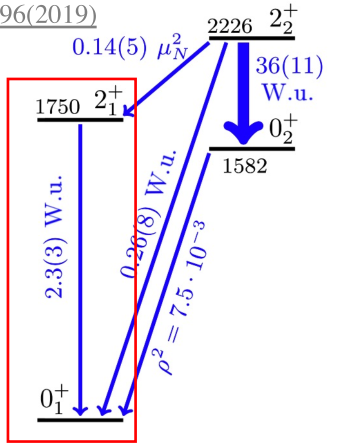




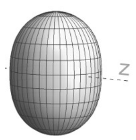
P. L.K, NDS68, 165(1993)

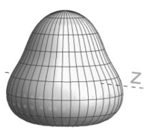


L. Iskra et al., PLB788, 396(2019)



C. Kremer et al., PRL117, 172503 (2016)





Nuclear structure experimental data on Ru/Zr β_n:

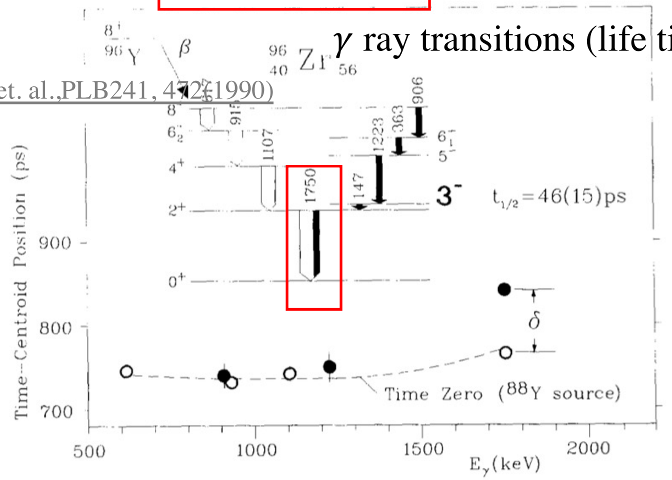
	β_2	$E_{2_1^+}$ (MeV)	β_3	$E_{3_1^-}$ (MeV)
^{96}Ru	0.154	0.83	-	3.08
^{96}Zr	0.062	1.75	0.202,0.235,0.27	1.90

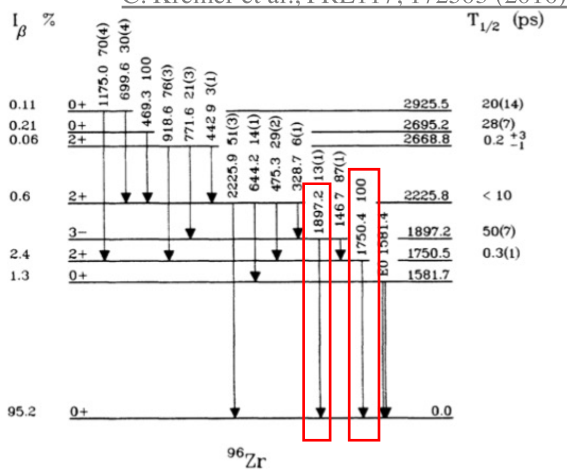
$$\beta_2 = \frac{4\pi}{3ZR_0^2}\sqrt{\frac{B(E2)\uparrow}{e^2}} \qquad \beta_3 = \frac{4\pi}{3ZR_0^3}\sqrt{\frac{B(E3)\uparrow}{e^2}}$$

Lower energy experiments show large $\beta_{2,Ru}$ and strong $\beta_{3,Zr}$

γ ray transitions (life time)

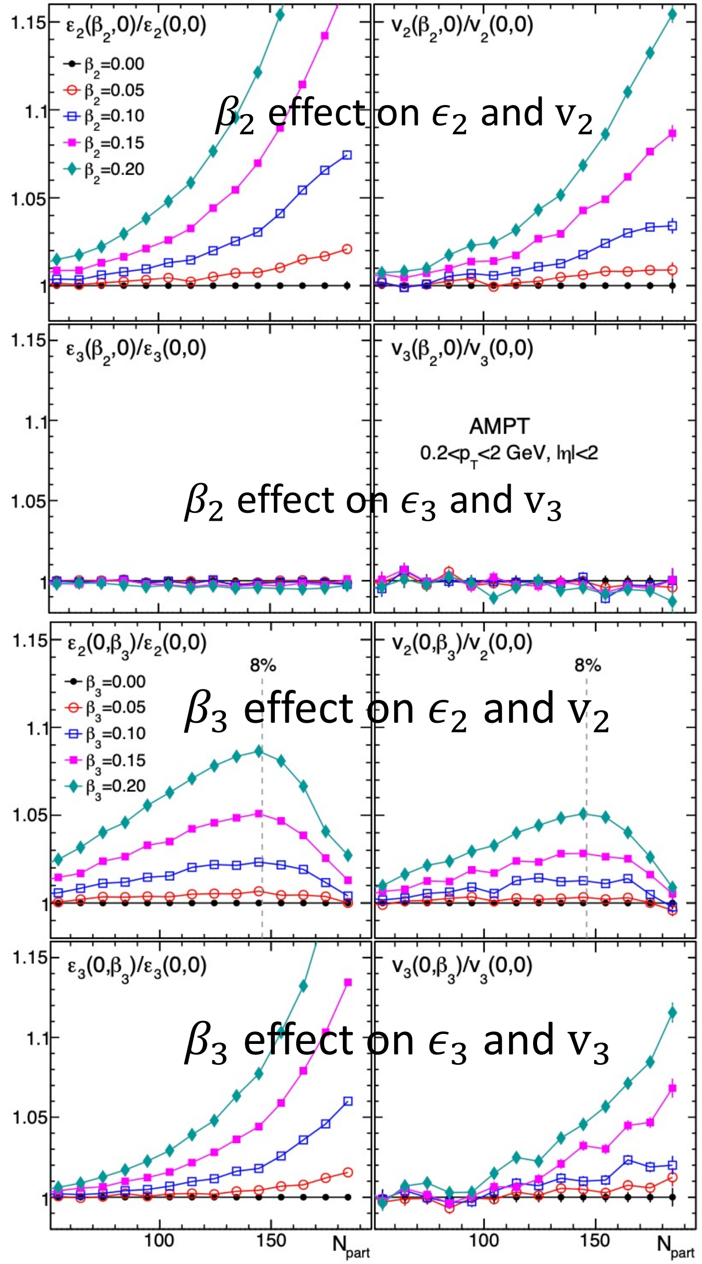
H. Ohm et. al.,PLB241, 472(1990)

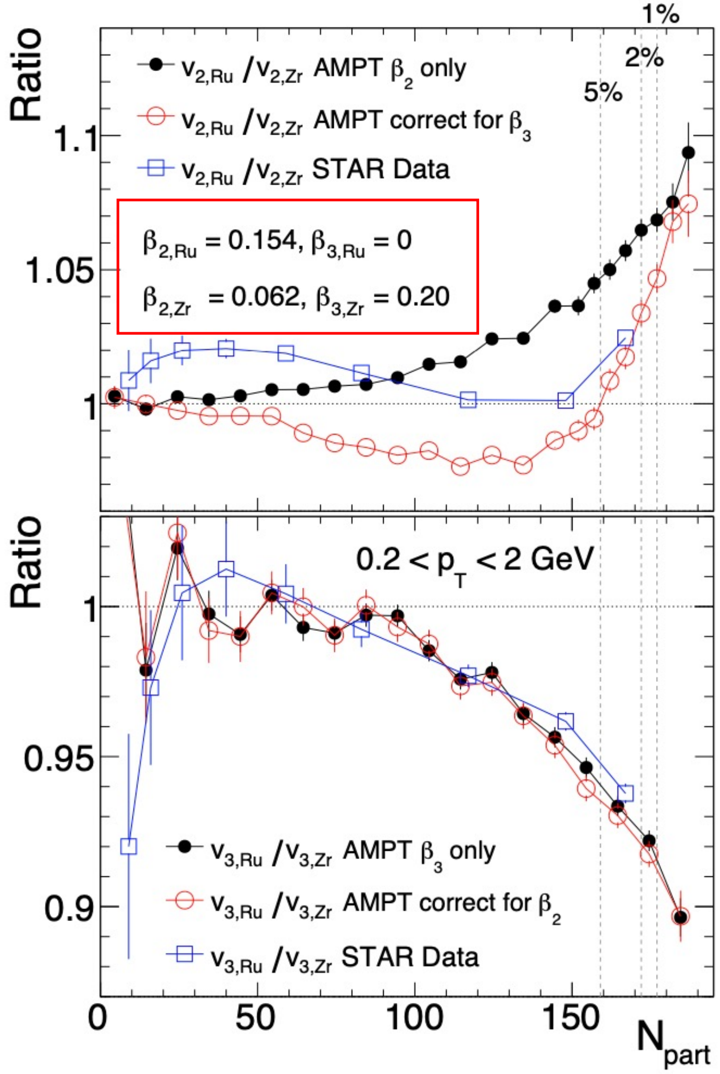




H. Mach et. al., PRC42R, 811(1990)

Evidence of quadrupole and octupole deformations in isobar

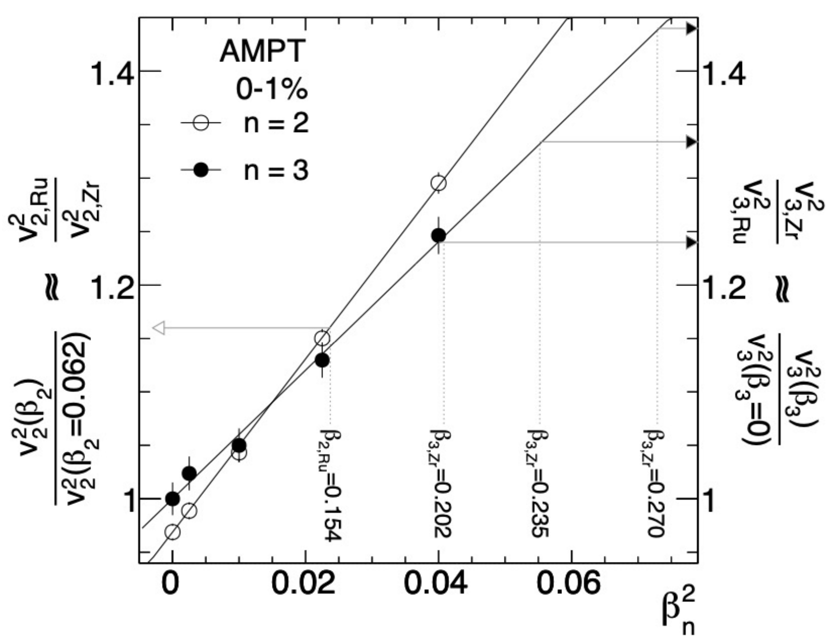




Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

C. Zhang and J. Jia, PRL128, 022301(2022)



Flow ratio ~ linear β_n^2 dependence

$$\frac{v^2_{2,\mathrm{Ru}}}{v^2_{2,\mathrm{Zr}}} \approx 1 + \frac{b_2}{a_2}\left(\beta^2_{2,\mathrm{Ru}} - \beta^2_{2,\mathrm{Zr}}\right) - \frac{b_{2,3}}{a_2}\beta^2_{3,\mathrm{Zr}}$$

$$\frac{v^2_{3,\mathrm{Ru}}}{v^2_{3,\mathrm{Zr}}} \approx 1 - \frac{b_3}{a_3}\beta^2_{3,\mathrm{Zr}} < 1$$

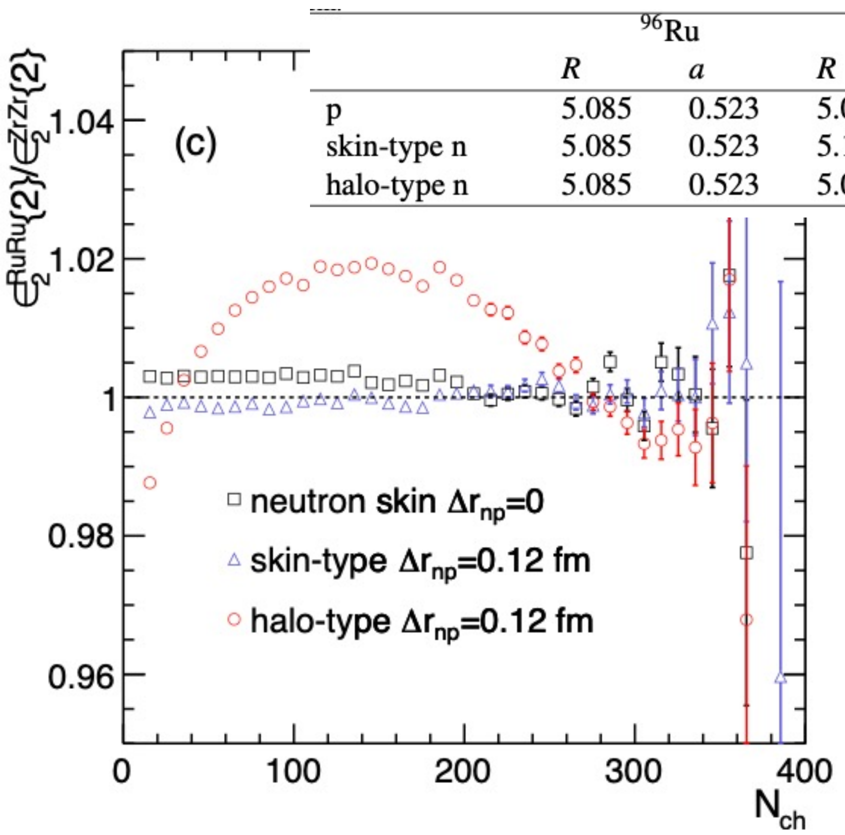
Cancelation expected in non-central collisions

G. Giacalone, J. Jia and C. Zhang, PRL127, 242301(2021)

Interplay of deformation and neutron skin in the v_n ratios

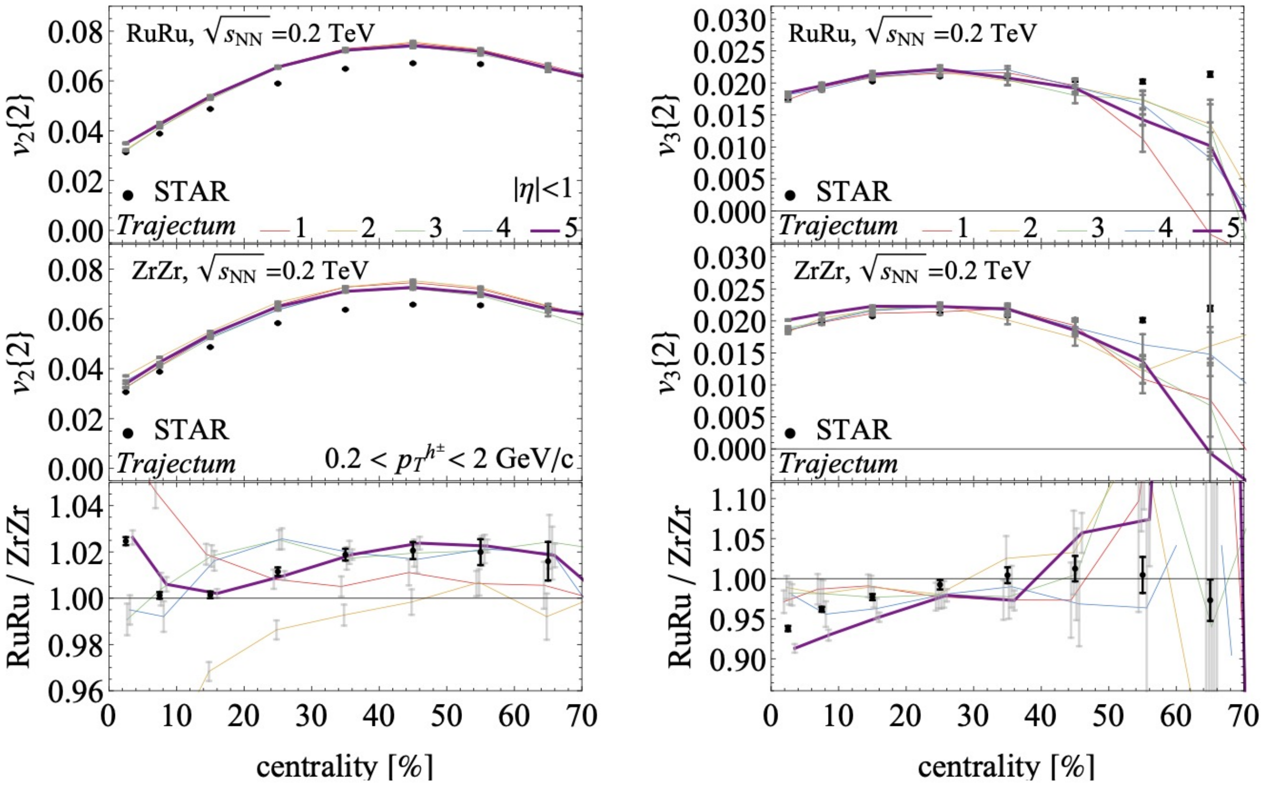
G. Nijs and W. Schee, arXiv:2112.13771v1

H.J. Xu et al., PLB819, 1136453(2021)



v_n ratio is sensitive to the neutron skin type (skin vs. halo).

model prefers halo type in Zr

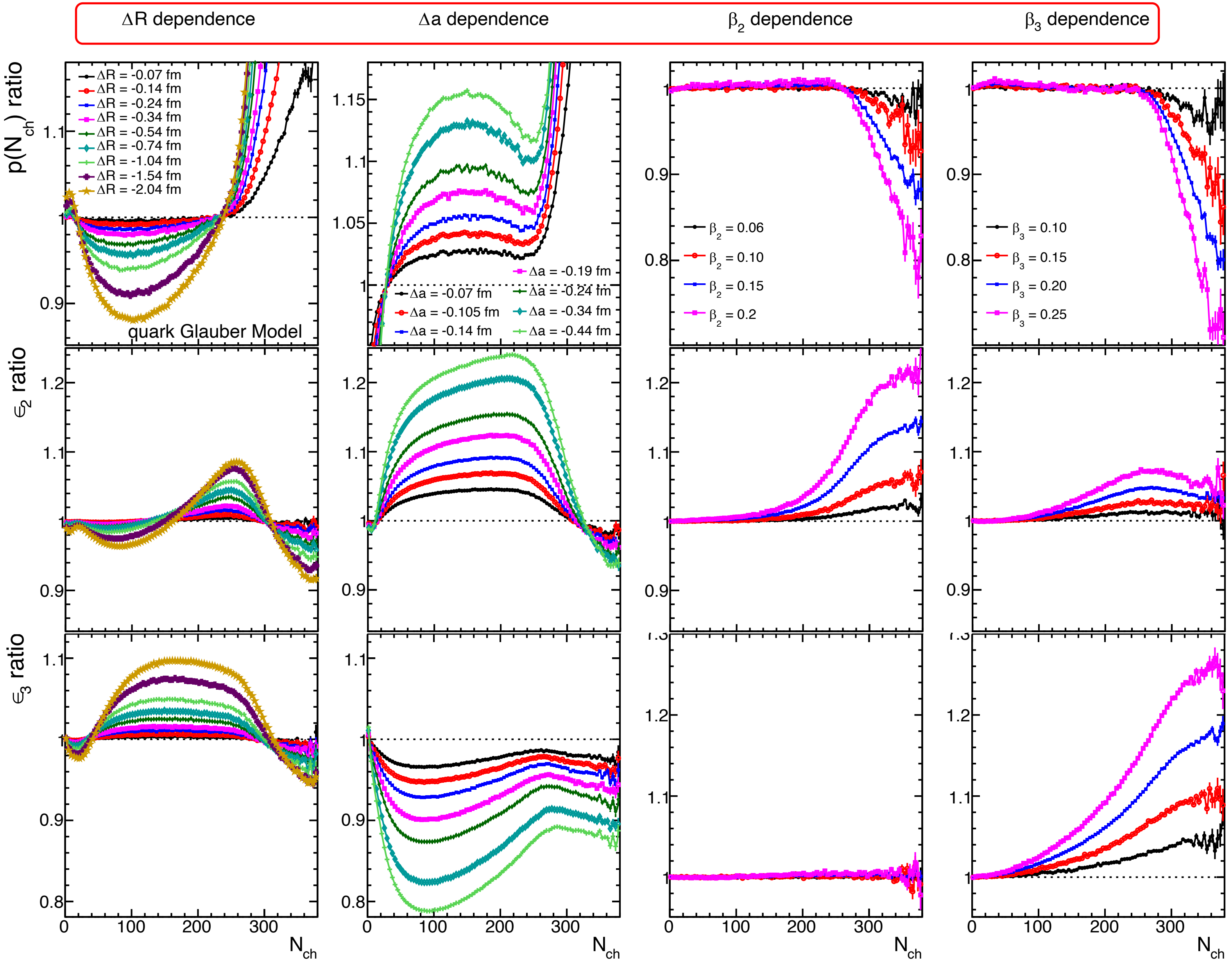


nucleus	R_p [fm]	σ_p [fm]	R_n [fm]	σ_n [fm]	β_2	β_3	σ_{AA} [b]
$^{96}_{44}$Ru(1)	5.085	0.46	5.085	0.46	0.158	0	4.628
$^{96}_{40}$Zr(1)	5.02	0.46	5.02	0.46	0.08	0	4.540
$^{96}_{44}$Ru(2)	5.085	0.46	5.085	0.46	0.053	0	4.605
$^{96}_{40}$Zr(2)	5.02	0.46	5.02	0.46	0.217	0	4.579
$^{96}_{44}$Ru(3)	5.06	0.493	5.075	0.505	0	0	4.734
$^{96}_{40}$Zr(3)	4.915	0.521	5.015	0.574	0	0	4.860
$^{96}_{44}$Ru(4)	5.053	0.48	5.073	0.49	0.16	0	4.701
$^{96}_{40}$Zr(4)	4.912	0.508	5.007	0.564	0.16	0	4.829
$^{96}_{44}$Ru(5)	5.053	0.48	5.073	0.49	0.154	0	4.699
$^{96}_{40}$Zr(5)	4.912	0.508	5.007	0.564	0.062	0.202	4.871

Hydro results within Trajectum framework describe data when both octupole deformation and larger neutron skin in ^{96}Zr are taken into account

Nuclear structure effect on the initial state

J. Jia and C. Zhang, arXiv:2111.15559v1



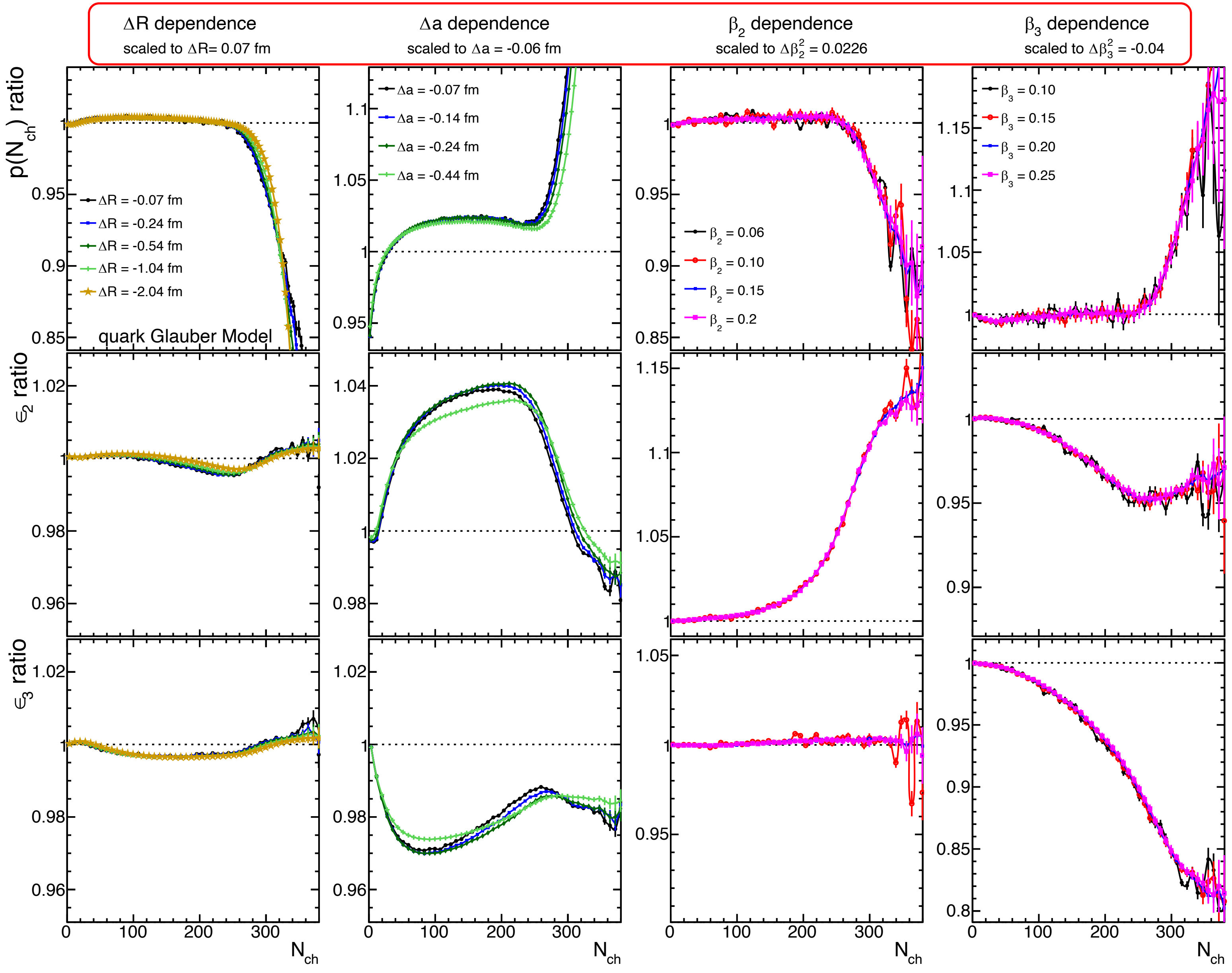
Species	β_2	β_3	a_0	R_0
Ru	0.162	0	0.46 fm	5.09 fm
Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

R_0 has some effect with unexpected big change
a_0 enhance it in mid-central
β_2 decrease it in central
β_3 decrease it in central

R_0 has some effect with unexpected big change
a_0 enhance ϵ_2 in mid-central
β_2 enhance ϵ_2 in from mid-central to central
β_3 enhance ϵ_2 in mid-central

R_0 has some effect with unexpected big change
a_0 decrease ϵ_2 in mid-central
β_2 has no effect on ϵ_3
β_3 enhance ϵ_3 in mid-central

Scaling approach to nuclear structure on the initial state



J. Jia and C. Zhang, arXiv:2111.15559v1

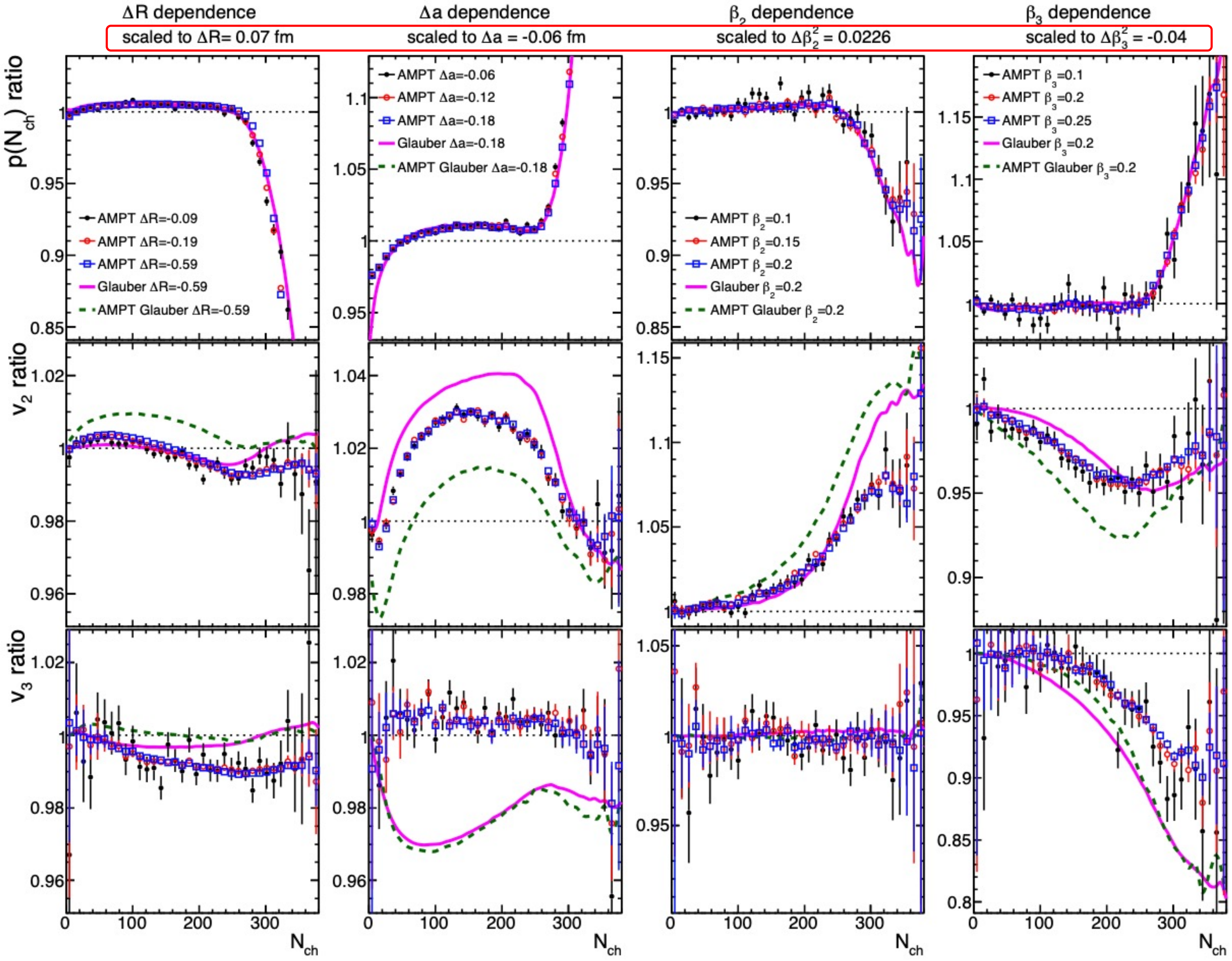
Is it linear?

Yes, only scale a constant value

nearly perfect scaling over the wide range of parameter values

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$

Scaling approach to nuclear structure



J. Jia and C. Zhang, arXiv:2111.15559v1

Species	β_2	β_3	a_0	R_0
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difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa_0	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

nearly perfect scaling over the wide range of parameter values

c_n can be determined more precisely by using a larger change of these parameters

Verifies the relation:

$$\mathcal{O} \approx b_0 + b_1\beta_2^2 + b_2\beta_3^2 + b_3(R_0 - R_{0,\,\mathrm{ref}}) + b_4(a - a_{\mathrm{ref}})$$

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

A direct algebra linked to neutron skin

Using relation for WS: $R^2 \equiv \langle r^2 \rangle \approx \left(\frac{3}{5}R_0^2 + \frac{7}{5}\pi^2 a^2\right) / \left(1 + \frac{5}{4\pi^2}\sum_n \beta_n^2\right)$

Neutron skin expressed by R and a parameters for nucleons and protons:

$$\Delta r_{np} \approx \frac{R^2 - R_p^2}{R(\delta+1)} \approx \frac{3\left(R_0^2 - R_{0,p}^2\right) + 7\pi^2\left(a^2 - a_p^2\right)}{\sqrt{15}R_0\sqrt{1 + \frac{7\pi^2}{3}\frac{a^2}{R_0^2}}\left(1 + \delta + \frac{5}{8\pi^2}\sum_n \beta_n^2\right)}$$

$$\delta = (N - Z)/A$$

The difference between two isobar systems can be expressed as:

$$\Delta(\Delta r_{np}) = \Delta r_{np,1} - \Delta r_{np,2} \approx \frac{\Delta Y - \frac{7\pi^2}{3}\frac{\bar{a}^2}{\bar{R}_0^2}\left(\frac{\Delta Y}{2} + \bar{Y}\left(\frac{\Delta a}{\bar{a}} - \frac{\Delta R_0}{\bar{R}_0}\right)\right)}{\sqrt{15}\bar{R}_0\left(1 + \bar{\delta} + \frac{5}{8\pi^2}\sum_n \overline{\beta_n^2}\right)}$$

where $Y \equiv 3\left(R_0^2 - R_{0,p}^2\right) + 7\pi^2\left(a^2 - a_p^2\right)$ $\quad \Delta x = x_1 - x_2 \quad \bar{x} = (x_1 + x_2)/2$

Can obtain skin diff. from ΔR_0 Δa for nucleons and known ΔR_0 Δa for protons

Example: H.J. Xu et. al., PLB819, 1136453(2021)

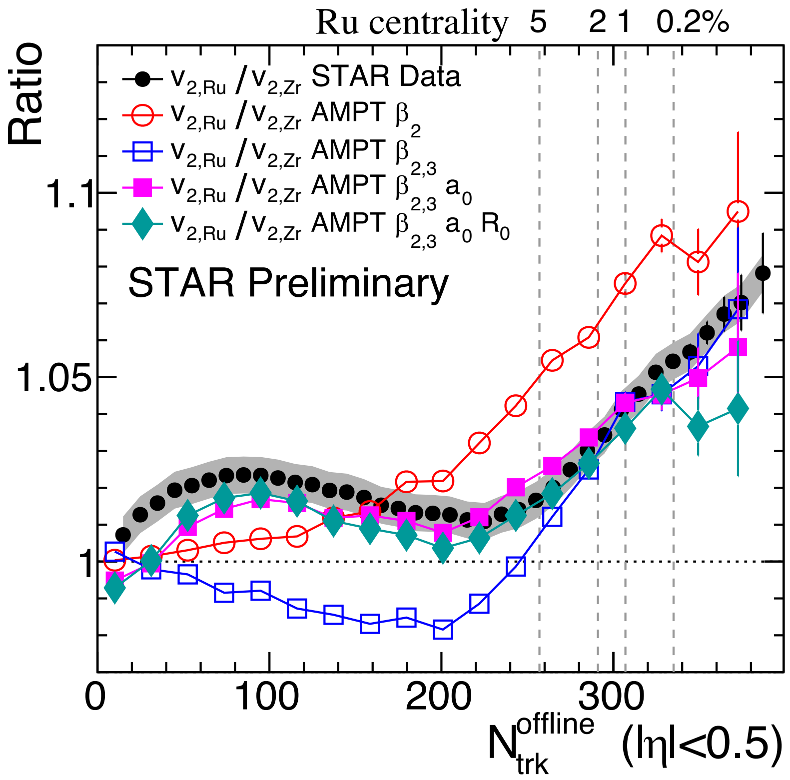
	^{96}Ru		^{96}Zr	
	R	*a*	*R*	*a*
p	5.060	0.493	4.915	0.521
n	5.075	0.505	5.015	0.574
p+n	5.067	0.500	4.965	0.556

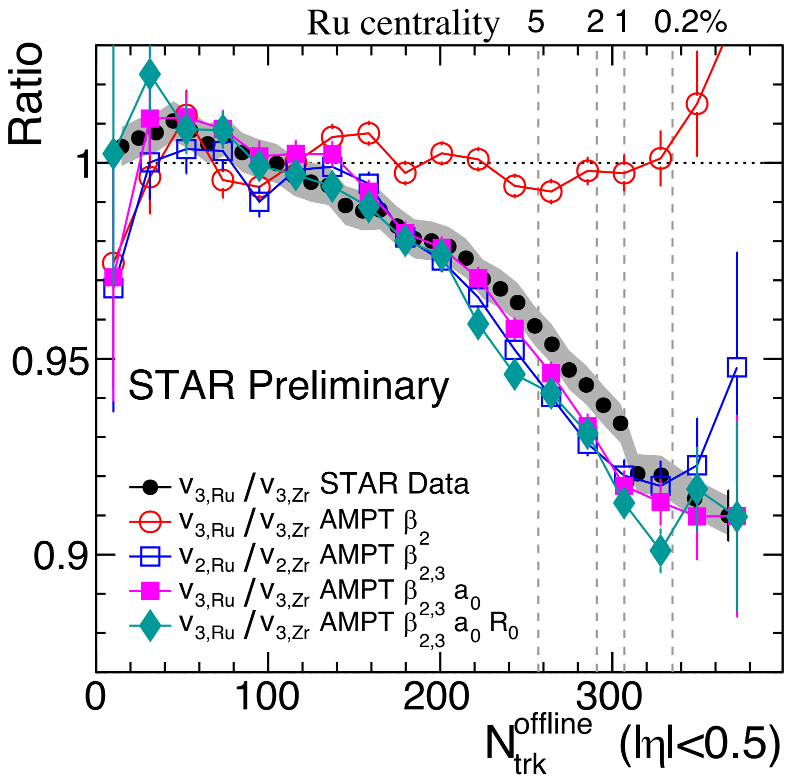
Direct calc.: $\Delta(\Delta r_{np})$=0.0296 fm – 0.1606 fm = -0.1310 fm

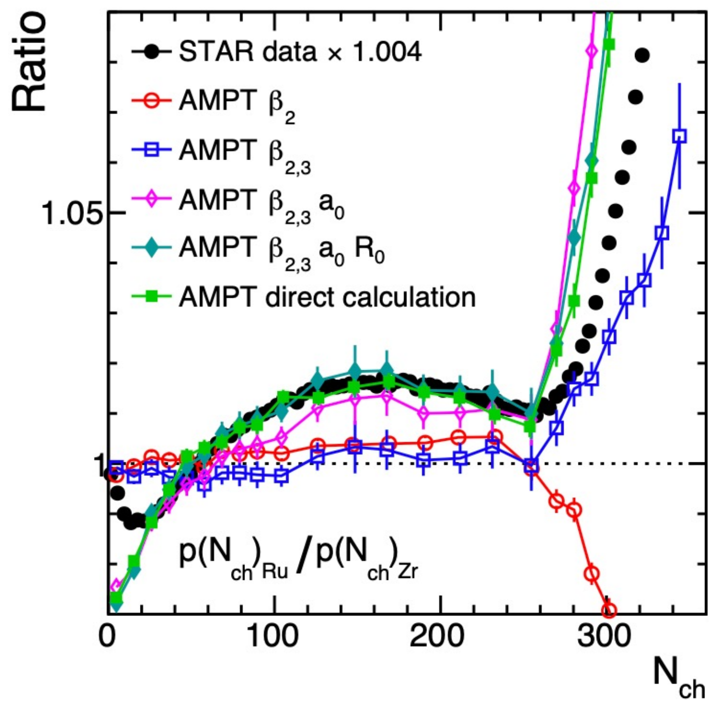
Formula: $\Delta(\Delta r_{np})$= -0.1319 fm

<1% difference

Nuclear structure via v_n ratio







Heavy-ion expectation:

$$v_2^2 = a_2 + b_2\beta_2^2 + b_{2,3}\beta_3^2, \quad v_3^2 = a_3 + b_3\beta_3^2$$

$$\frac{v_{2,\mathrm{Ru}}^2}{v_{2,\mathrm{Zr}}^2} \approx 1 + \frac{b_2}{a_2}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \frac{b_{2,3}}{a_2}\beta_{3,\mathrm{Zr}}^2$$

$$\frac{v_{3,\mathrm{Ru}}^2}{v_{3,\mathrm{Zr}}^2} \approx 1 - \frac{b_3}{a_3}\beta_{3,\mathrm{Zr}}^2 < 1$$

Cancelation expected in non-central collisions

1) Nonmonotonic trends: in v_2 and p(Nch) ratios

2) v_3 ratio: strong decrease from $\beta_{3,Zr}$ with negligible $\beta_{2,Ru}$ distortion

✓ The large differences of v_2 and v_3 suggest $\boldsymbol{\beta_{2,Ru} \gg \beta_{2,Zr}}$ **and** $\boldsymbol{\beta_{3,Ru} \ll \beta_{3,Zr}}$ **.**

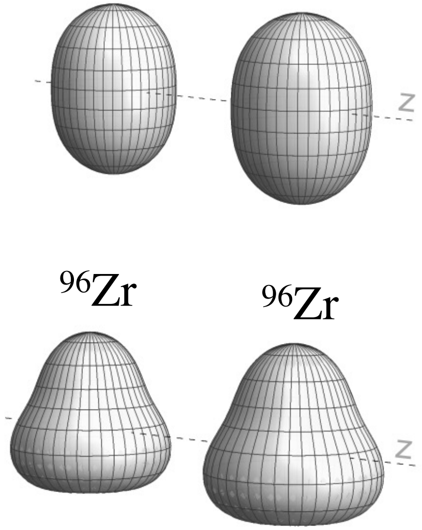
Direct indication of octupole deformation in heavy-ion collisions.

Nuclear structure via $[p_T]$ variance ratio

J. Jia, PRC105, 014905(2022) (Editors' Suggestions)

^{96}Ru ^{96}Ru

^{96}Zr ^{96}Zr



$R = 5.09$ fm
$a_0 = 0.46$ fm
$\beta_2 = 0.162$
$\beta_3 \sim 0$

$R = 5.02$ fm
$a_0 = 0.52$ fm
$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

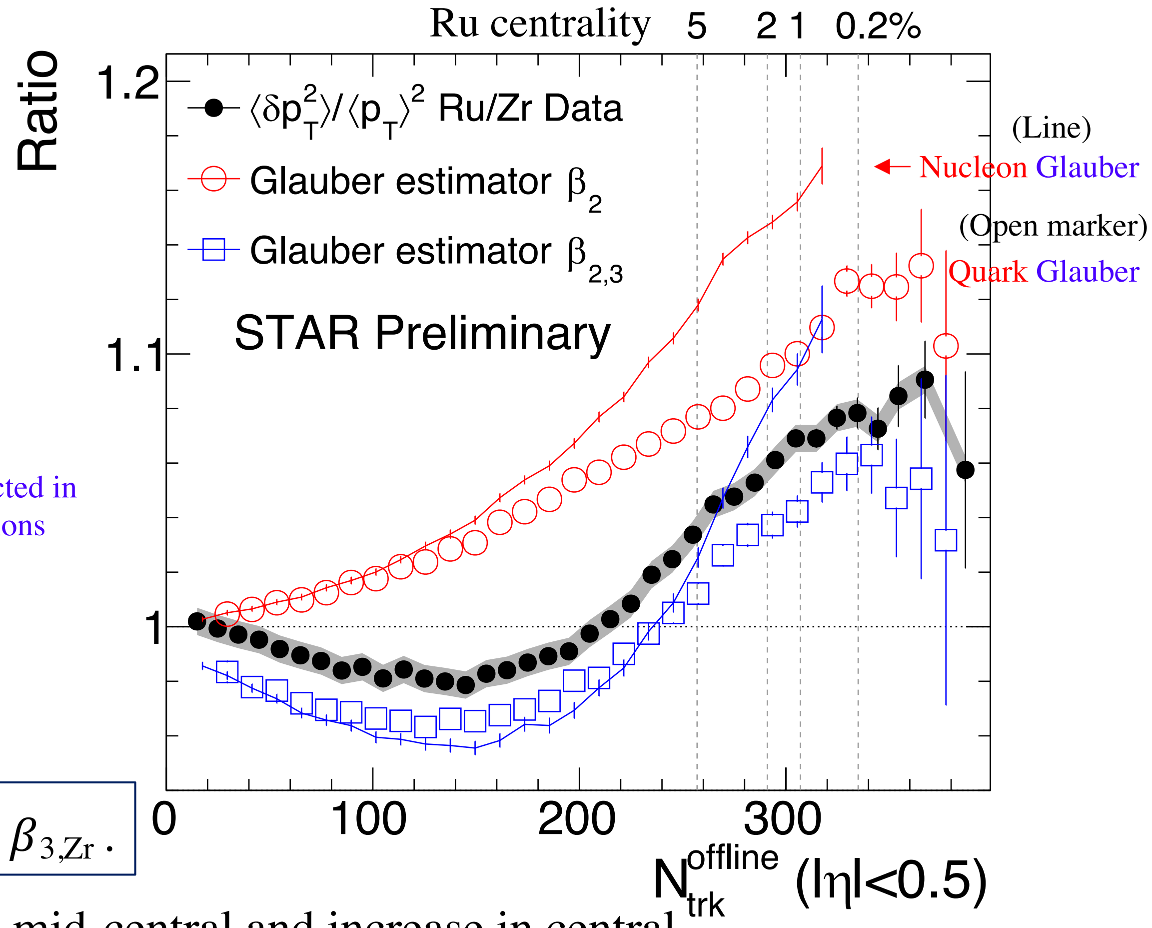
Heavy-ion expectation:
$$\left\langle (\delta[p_\mathrm{T}]/[p_\mathrm{T}])^2 \right\rangle = a_0 + b_0\beta_2^2 + b_{0,3}\beta_3^2$$

$$\frac{\langle \delta p_T^2\rangle_{\mathrm{Ru}}}{\langle \delta p_T^2\rangle_{\mathrm{Zr}}} \approx 1 + \frac{b_0}{a_0}(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2) - \frac{b_{0,3}}{a_0}\beta_{3,\mathrm{Zr}}^2$$

Cancelation expected in non-central collisions

$$\left\langle (\delta[p_\mathrm{T}]/[p_\mathrm{T}])^2 \right\rangle \propto \left\langle (\delta d_\perp/d_\perp)^2 \right\rangle = \langle \delta_d^2 \rangle + \left\langle p_0(\Omega_1,\Omega_2,\gamma)^2 \right\rangle \beta_2^2$$

✓ $\beta_{2,\mathrm{Ru}} \gg \beta_{2,\mathrm{Zr}}$ and $\beta_{3,\mathrm{Ru}} \ll \beta_{3,\mathrm{Zr}}$.



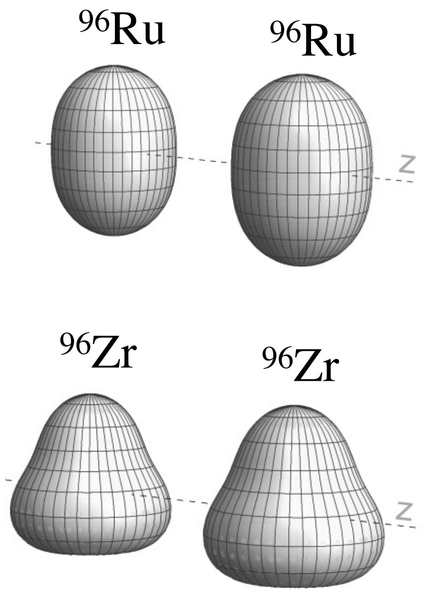
1) Nonmonotonic trend: large suppression in mid-central and increase in central

2) Enhancement from mid-central ⇒ large $\beta_{2,\mathrm{Ru}}$

3) Large suppression in mid-central ⇒ strong octupole $\beta_{3,\mathrm{Zr}}$

Variance of $[p_T]$ fluctuations can also be used to constrain the nuclear deformation.

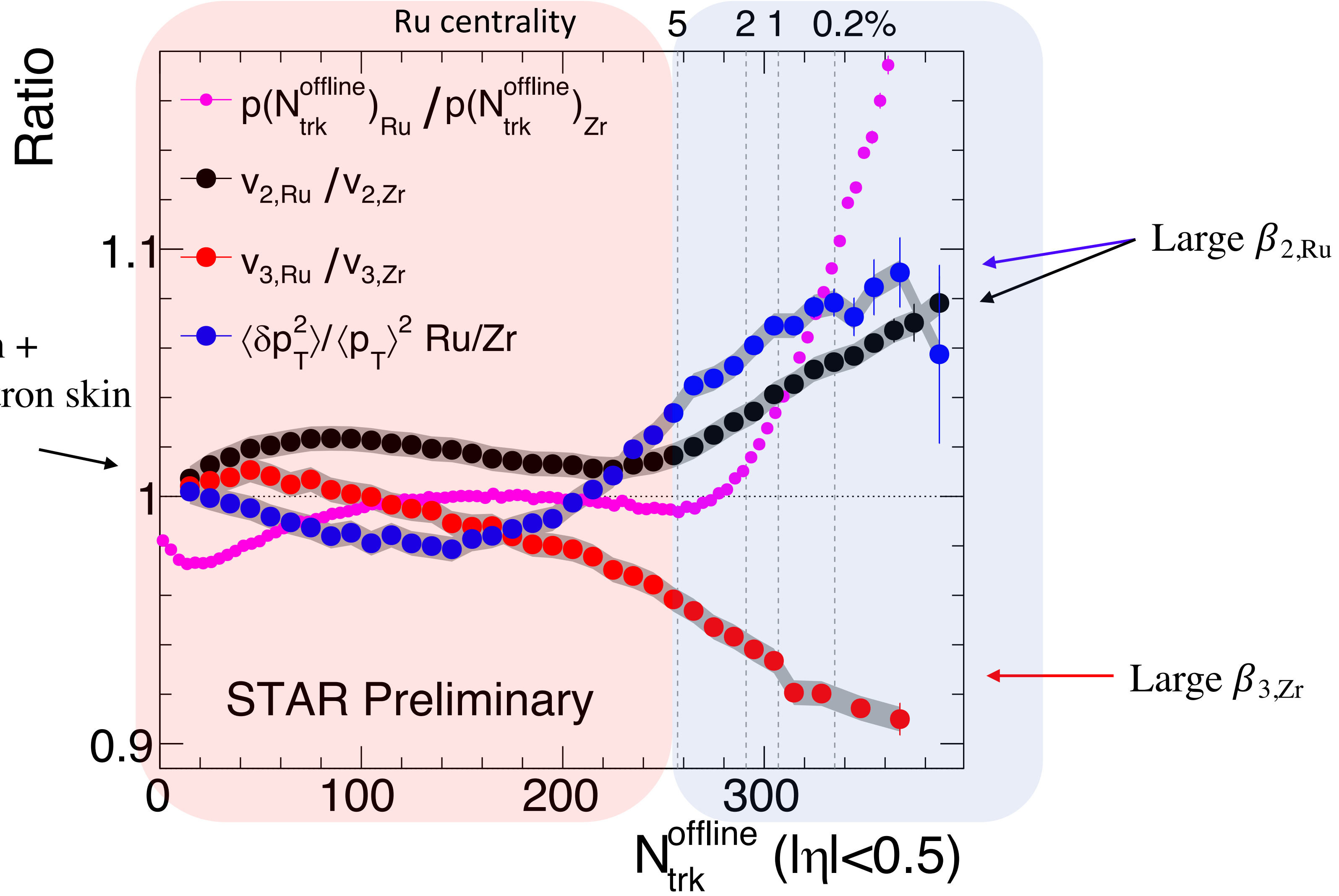
Flow, $[p_T]$ variance and multiplicity ratio



$R = 5.09$ fm
$a_0 = 0.46$ fm
$\beta_2 = 0.162$
$\beta_3 \sim 0$

$R = 5.02$ fm
$a_0 = 0.52$ fm
$\beta_2 = 0.06$
$\beta_3 = 0.20 - 0.27$

Nuclear deformation +
Radial structure, e.g., neutron skin



M. S. Abdallah et al. (STAR), PRC105, 014901(2022)
Q. Shou, Y.G. Ma et al., PLB749, 215(2015)
H.L. Li and H.J. Xu et al., PRC98, 054907(2018)
H.J. Xu et al., PLB819, 1136453(2021)
J. Jia, PRC105, 014905(2022) (Editors' Suggestions)
C. Zhang and J. Jia, PRL128, 022301(2022)
G. Giacalone, J. Jia and V. Soma, PRC104, L041903(2021)

Ratio of any bulk observables can image the shape of the nuclei.

Conclusions and Outlooks

Conclusions:

1. v_n-[p_T] correlations

- ✓ STAR results show strong suppression and sign-change for n=2 in UU, but no difference for n=3.
- ✓ Main features are robust against p_T selection and nonflow effect from mid-central to central.
- ✓ Deformation influences collisions over a wide centrality range: mid-central to central.
- ✓ Qualitatively described by TRENTo, CGC+hydro and AMPT models: prefer a quadrupole β_2 value around 0.3
- ✓ Help to constrain initial conditions, study the initial state momentum correlations, triaxiality and nucleon size.

2. [p_T] fluctuations

- ✓ Deformation enhance the variance and skewness; a sign-change in kurtosis.
- ✓ Study quadrupole β_2 by the data model comparison in conjunction with v_n-[p_T] correlations.

3. Use bulk observables to decode the isobar nuclear structure

- ✓ The ratios of v_2, v_3, $\langle \delta p_T^2 \rangle$ and multiplicity have large deviation from one implying:

  $\beta_{2,Ru} \gg \beta_{2,Zr}$, $\beta_{3,Ru} \ll \beta_{3,Zr}$, and radial structure, e.g., neutron skin in ^{96}Zr
- ✓ Isobar collisions are a new tool to study the nuclear structure.
- ✓ This is the direct observation of ^{96}Zr octupole deformation/collectivity using heavy-ion collisions.

Conclusions and Outlooks

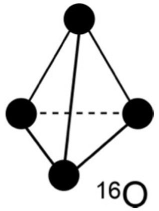
Outlooks:

1. **Isobar collisions open up new opportunity to study nuclear structure at a very short time scale ($\sim 10^{-23}$s) through heavy-ion collisions.**
   - Future deformed-system scan at LHC and NICA
   - Species with well known deformation will be useful to better understand the systematics and establish the efficacy of this approach

2. **RHIC/LHC O+O runs help to decipher cluster structures in relativistic heavy-ion collider.**

Single-Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)
100	200	1 week	O+O	400 M 200 M (central)

(RUN21 took all the data we wanted and more)



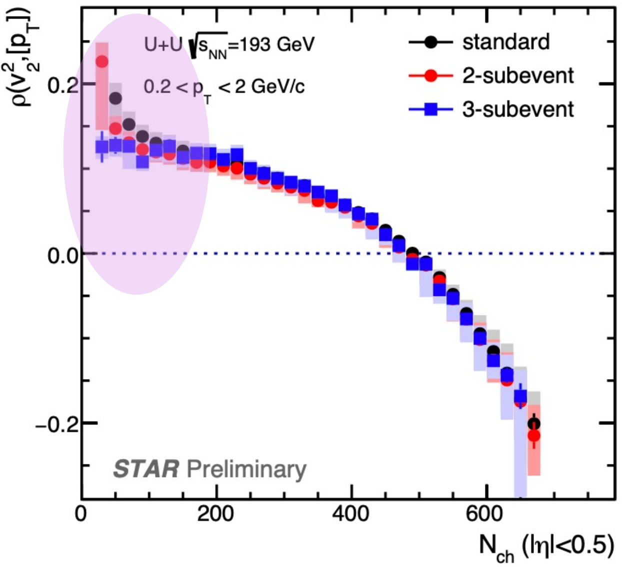
Study of α-cluster at RHIC and LHC

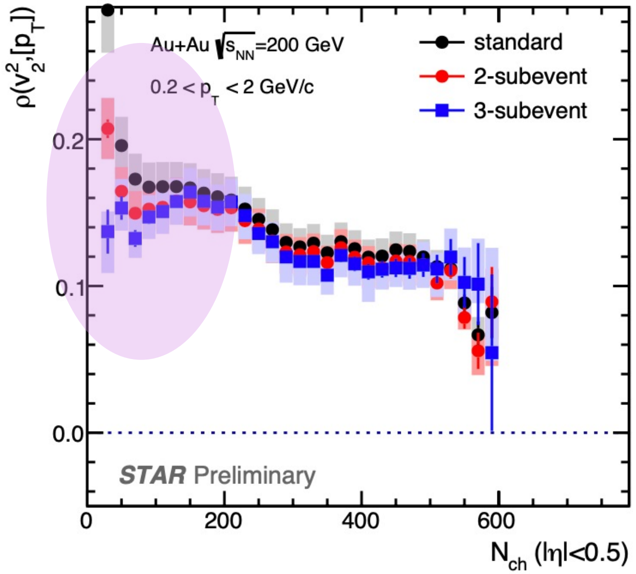
W.B. He, Y.G. Ma et al., PRL113, 032506(2014); W. Broniowski and E.R. Arriola, PRL112, 112501(2014); P. Bozek et al., PRC90, 064902(2014); S. Zhang, Y.G. Ma et al., PRC95, 063904(2017); M. Rybczynsko et al., PRC97, 034912(2018); Y.A. Li, S. Zhang and Y.G. Ma, PRC102, 054907(2020); N. Summerfield et al., PRC104, L041901(2021);

Thank you for listening and also many thanks to WWND2022

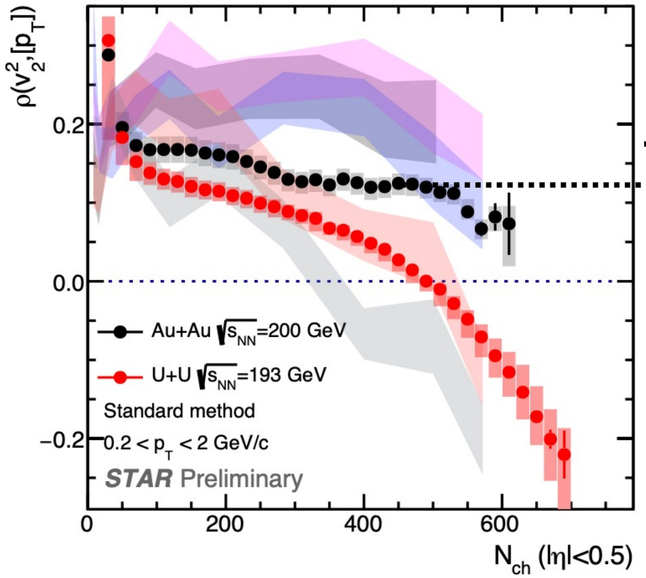
The effects of nonflow and different p_T selection

Full event	Two-subevent		Three-subevent		
$v_2, p_T\ \lvert\eta\rvert < 1.0$	$v_2^A\ \eta < -0.1$	$v_2^B\ \eta > 0.1$	$v_2^A\ \eta < -0.35$	$v_2^B \lvert\eta\rvert < 0.3$	$v_2^C \eta > 0.35$

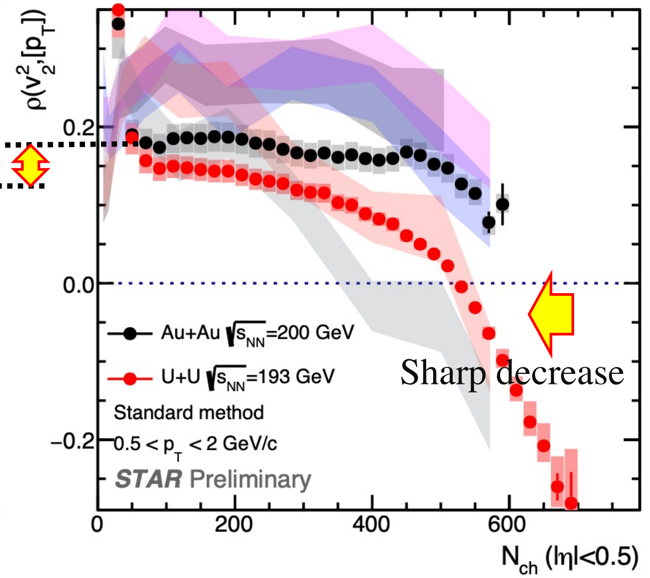




0.2< p_T < 2 GeV/c



0.5< p_T < 2 GeV/c



Standard method is consistent with subevent methods at high N_{ch}.

Subevent methods could decrease non-flow contributions in peripheral region.

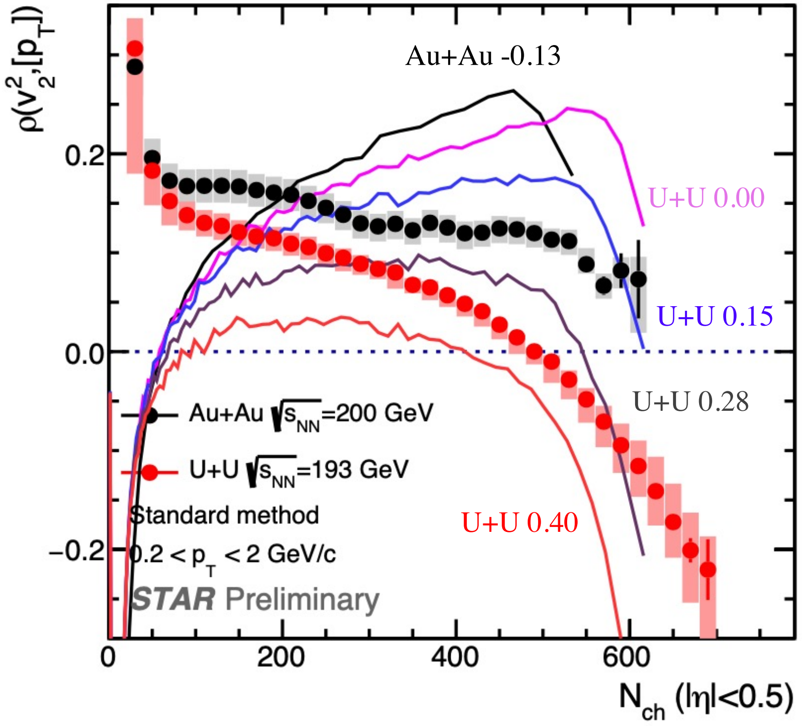
Non-flow doesn't affect $\rho(v_n^2, [p_T])$ mid-central and central.

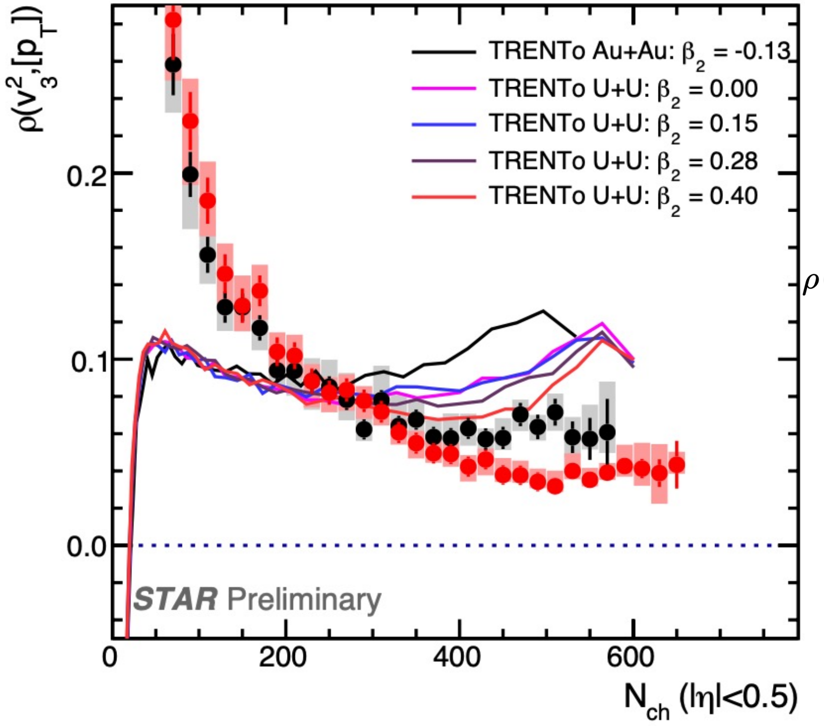
Features are same for different p_T selection.

Compare to TRENTo initial-state model

TRENTo: private calculation provided by Giuliano Giacalone (PRC102, 024901(2020), PRL124, 202301(2020))

Calculated via predictor with assumption: $v_n \propto \epsilon_n$, $[p_T] \propto \frac{E}{S}$ ⇒ $\rho(v_n^2, [p_T]) \sim \frac{\langle \epsilon_n^2 \delta \frac{E}{S} \rangle}{\sqrt{\mathrm{var}(\epsilon_n^2) \langle \delta \frac{E}{S} \delta \frac{E}{S} \rangle}}$



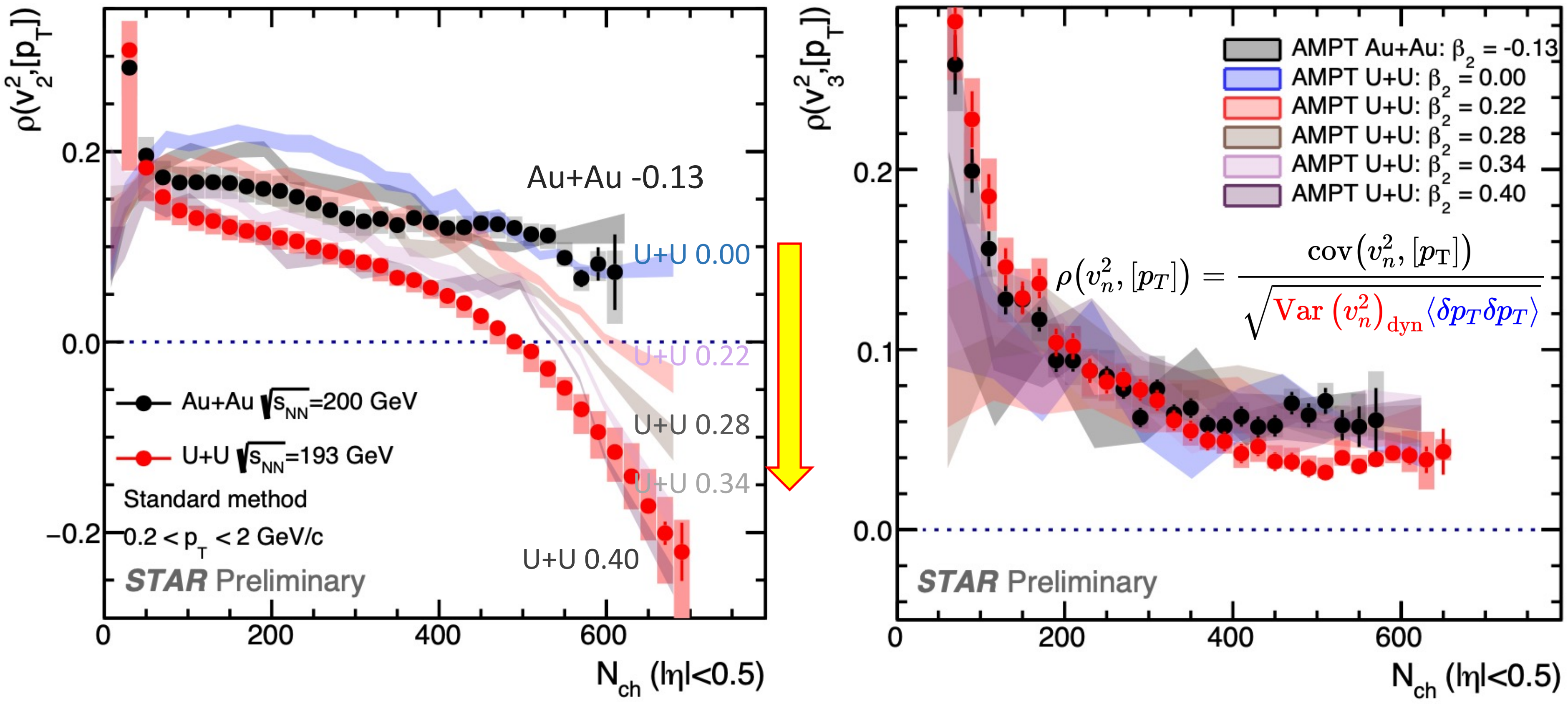


$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}\,(v_n^2)_{\mathrm{dyn}} \langle \delta p_T \delta p_T \rangle}}$$

- Trento does not describe data but shows an hierarchical β_2 dependence for correlations
- Trento shows sign-change from Uranium deformation, prefers 0.28< β_2 <0.4
- Trento shows that v_3^2-$[p_T]$ correlations are insensitive to deformation.

Compare to transport AMPT model

J. Jia, S. Huang and C. Zhang, PRC105, 014906(2022)



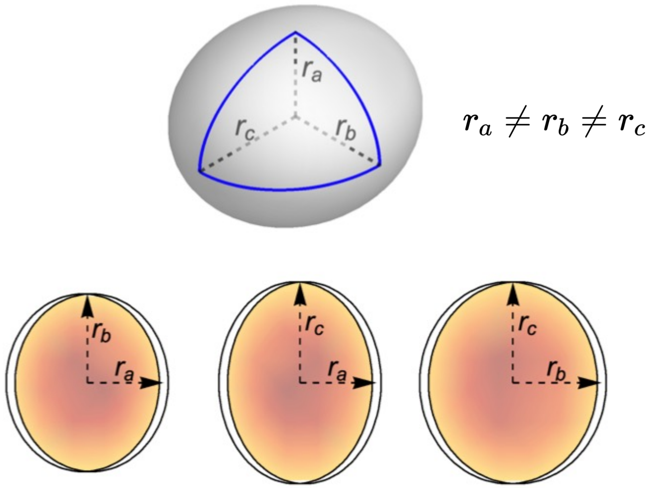
- AMPT shows a clear β_2 dependence in U+U $\rho(v_2^2,[p_T])$ while not in $\rho(v_3^2,[p_T])$.
- AMPT supports the sign-change of $\rho(v_2^2,[p_T])$ in U+U is due to deformation effect .
- AMPT favors 0.28< β_2 <0.4 for uranium with large uncertainties.

Central collisions: evidence of the triaxial structure of ^{129}Xe at LHC

Triaxial

J. Jia, arXiv:2109.00604v1

$\beta_2 = 0.25, \cos(3\gamma) = 0$

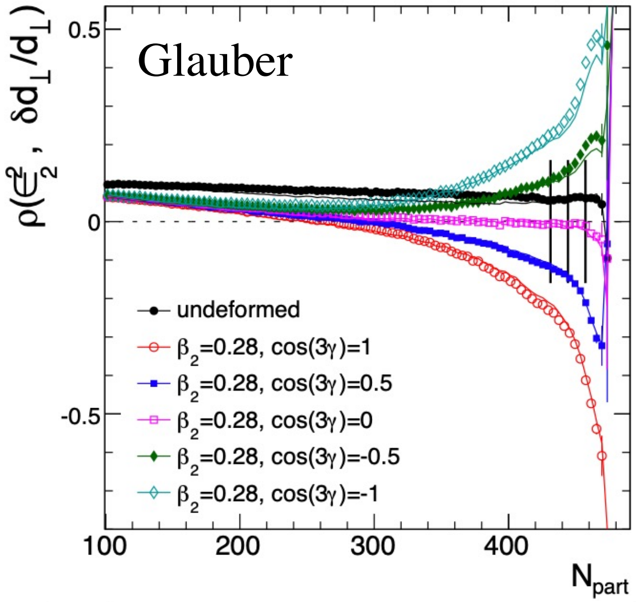


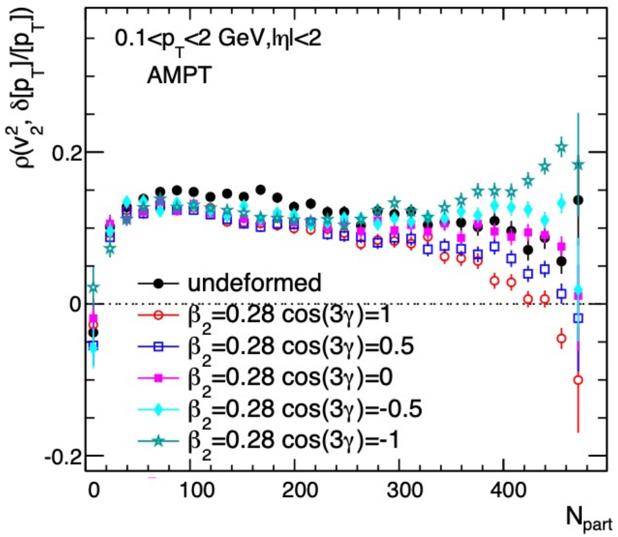
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1 + e^{[r - R(\theta,\phi)/a_0]}}$$

$$R(\theta,\phi) = R_0(1 + \beta_2[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)])$$

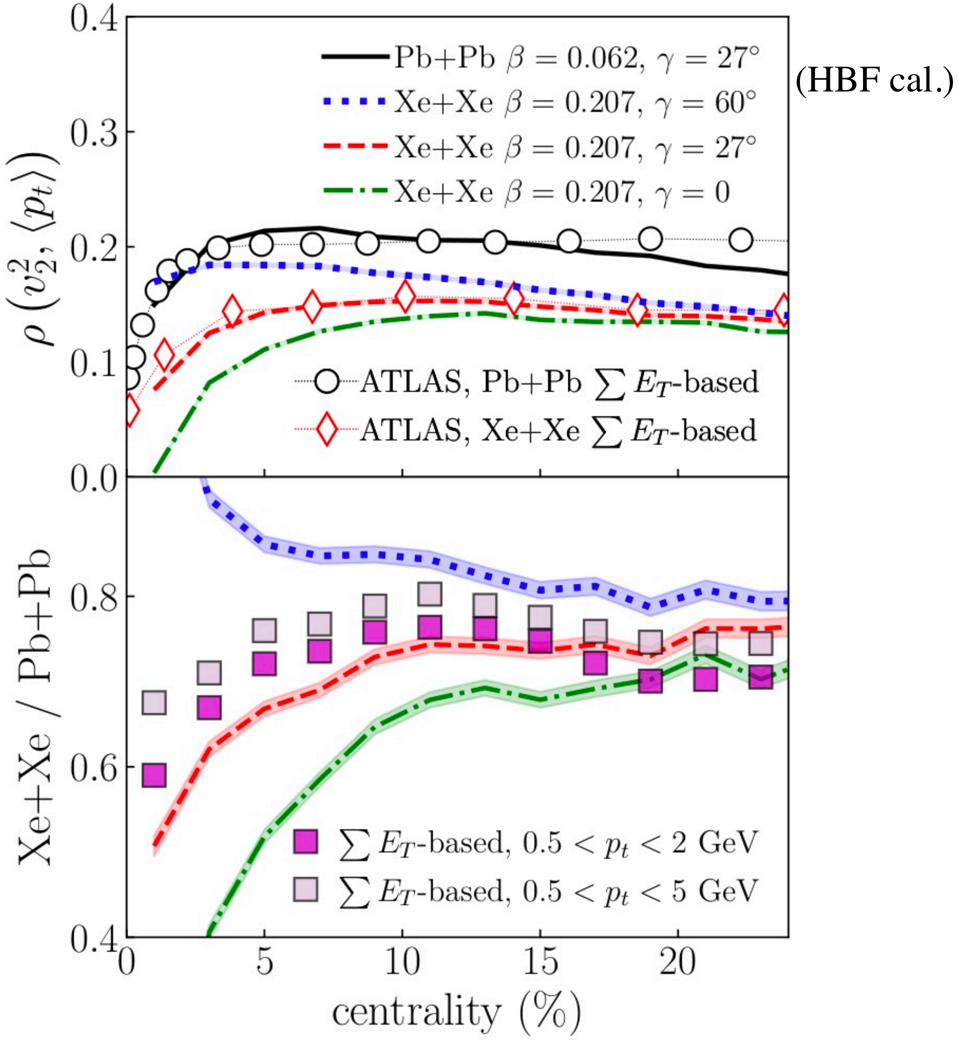
$$\left\langle \varepsilon_2^2 \frac{\delta d_\perp}{d_\perp} \right\rangle \approx -\frac{3\sqrt{5}}{28\pi^{3/2}} \cos(3\gamma)\beta_2^3$$

Could isolate the γ dependence





B. Bally, M. Bender, G. Giacalone and V. Soma, PRL128, 082301(2022)



^{129}Xe with $\gamma = 27°$ better describe the ATLAS data